Master Thesis
M.Sc. Renewable Energy Engineering

Utilizing Solar Photovoltaics to Improve Primary Health Care in Rural and Tribal Regions of Developing Nations

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Abstract

This report focuses on rural and tribal regions of India to evaluate the ways that solar photovoltaic technology can supplement their lack of energy access, in an effort to improve the health care available to those communities. The report examines three separate case studies that have been carried out in India: the implementation of solar photovoltaic systems into primary health centers in rural parts of southern India to combat issues of intermittent or non-existent grid connected electricity, the deployment and analysis of solar direct drive vaccine refrigeration systems in these same areas to preserve the potency of vaccines and medicines needed by these communities, as well as an examination of a proposal for a solar powered boat ambulance to assist in providing primary health care, supplies, and transport to isolated tribal communities in eastern India.

The study on the primary health centers has shown that the implementation of solar systems in these facilities has lead to an average 31% savings in monthly electricity bills and equal reduction in demand from electricity from the grid, while increasing their overall reliability of electricity access. The solar direct drive vaccine refrigeration field study has revealed that these systems are capable of keeping their contents within the required temperature limits in the field, and surveys have shown they have many preferably qualities when compared to conventional units. Finally the study of the solar powered boat ambulance has revealed that the latest evaluated design would be able to service a distance of 25 kilometers in the month of the worst solar irradiation. This would adequately serve the tribal population in the region and would aid in combatting the poor conditions and undesirable health practices currently being implemented there.

The analysis of these cases involves the use MATLAB and Simulink software to determine the capabilities of the technologies used and the benefits from their implementation. The analyses reveal the potential to improve patient outreach and overall health of the communities in these isolated region by filling the gaps in their current energy demand with solar photovoltaics. It is the hope that these learnings can serve as a reference for future projects in India and other developing nations around the world.

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List of Acronyms & Abbreviations

PV photovoltaic

SELCO Solar Electric Light Company

WHO World Health Organization

UN United Nations

USD United States Dollar

GNI gross national income

MPI multidimensional poverty index

PHCs primary health centers

NRHM National Rural Health Mission

SC subcenters

CHC community health centers

IEA International Energy Agency

PM particulate matter

CODEV Cooperation & Development Center

EPFL Ecole Polytechnique Fédérale de Lausanne

LCOE levelized cost of energy

NREL National Renewable Energy Laboratory

DC direct current

DNI Direct Normal Irradiance

DHI Direct Horizontal Irradiance

GHI Global Horizontal Irradiance

NGO non-governmental organization

OPD outpatient department

IPD inpatient department

OT operation theater

LED Light Emitting Diode

INR Indian rupee

CDC United States' Centers for Disease Control and Prevention

VFC Vaccines for Children

EPI Expanded Program on Vaccination

UNICEF United Nations Children's Fund

ILR ice lined refrigerator

SDD solar direct drive

OVHA Orissa Voluntary Health Association

BASAID Basic Aid

NASA National Aeronautic and Space Administration

SOC State of Charge

Li Lithium

Si Silicon

P Phosphorous

B Boron

W Watt

kW kilowatt

Ah Ampere-hour

m Meter

km kilometer

L Liter

hr Hour

kWh Kilowatt-hour

1 Introduction & Scope of Study

As the world moves further into the 21st century, and onward with technological advancements, a large portion of humans across the globe still lack access to basic health care, especially those who live in rural and tribal areas of economically developing countries. The shortage of these fundamental services results in rampant disease, malnutrition, and dangerous health practices among these populations.

A major reason for the deficiency of health treatment in these areas is the absence of the energy needed to utilize healthcare equipment, properly store medicines and vaccines, and bridge the geographic gaps that separate patients from the medical care they need. Until the energy issue is addressed this problem will persist. Energy access is also necessary to facilitate the distribution and administration of medical supplies, knowledge, and personnel which are essential in providing quality care to those who need it.

This report analyzes some of the ways that solar photovoltaic (PV) technology can supplement this lack of energy access to improve the primary health care available to these communities. The current global situation will be examined, followed by a detailed look into three separate case studies that have been carried out in coordination with the Solar Electric Light Company (SELCO) Foundation located in Bangalore, India. India has been chosen as the country of study due to the opportunities presented there, as well as its unique position as a country undergoing massive amounts of development in recent years.

The three projects that will be detailed are:

1. The implementation of solar photovoltaic systems into primary health centers in rural parts of the south India to combat issues of intermittent or non-existent grid connected electricity.
2. The deployment and analysis of solar direct drive vaccine refrigeration systems in these same areas to preserve the potency of vaccines and medicines needed by the communities.
3. An examination of a proposal for a solar powered boat ambulance to assist in providing primary health care to isolated tribal communities in eastern India.

The objective of this report is to evaluate these separate case studies to determine the effectiveness of using solar PV technology to help overcome the mentioned limitations of primary health care in these areas. In addition, the report aims to document the learnings from these experiences in the hope that due to the wide array of geographic and socio-economic situations in India, the qualitative analyzes of these case studies can serve as a reference for future projects in India, as well as other regions in need around the globe.

To begin this process it is required to understand the current situation of primary health care in rural and tribal areas of developing nations, and in particular that of India.

2 Rural Health in Developing Countries

2.1 Introduction to Rural Health

In 1978 during the Alma-Ata conference in what is now Kazakhstan, the World Health Organization (WHO) declared that:

> health, which is a state of complete physical, mental and social wellbeing, and not merely the absence of disease or infirmity, is a fundamental human right and that the attainment of the highest possible level of health is a most important world-wide social goal ... The existing gross inequality in the health status of the people particularly between developed and developing countries as well as within countries is politically, socially and economically unacceptable and is, therefore, of common concern to all countries [3].

Nearly 40 years later, there have been immense improvements in the health of citizens around the globe, however there is still much more work that needs to be done. The discrepancies in public health and health care services between developed and developing nations that was seen in 1978 is still evident today.

The United Nations (UN) classifies countries based on their per capita gross national income (GNI). Countries with less than $[1]1,035 GNI per capita are classified as *low-income countries*, those with between $1,036 and $4,085 as *lower middle income countries*, those with between $4,086 and $12,615 as *upper middle income countries*, and those with incomes of more than $12,615 as *high-income countries*. For the purposes of this report *developing countries* will be defined as those countries which have either lower middle or low-income economic classifications [1].

A paper published in the New York Academy of Sciences reported in 2008 that developing countries account for 90% of the global instances of disease, but only 12% of the global spending on health. They go on to report that developed countries spend nearly 100 times on health per capita than their developing counterparts. There is also a direct correlation between the economic status of a country, and the amount of doctors, nurses, and hospital beds available to the general population as can be seen in Figure 1 [4].

Country grouping	Hospital beds per 10,000 population	Doctors per 1000 population	Nurses per 1000 population
Economic group			
Low-income countries	9	0.49	0.83
Lower middle-income countries	21	0.97	1.45
Upper middle-income countries	41	2.10	3.81
High-income countries	57	2.67	8.16
WHO region			
Africa	<1	0.21	0.93
Americas	25	1.94	4.88
Eastern Mediterranean	13	0.74	1.11
Europe	64	3.2	7.43
Southeast Asia	9	0.52	0.81
Western Pacific	31	1.1	1.7
World	26	1.23	2.56

Figure 1: Availability of Health Services Around the World [4]

The poorer a country is, the less these resources and trained personnel are available to them.

The population of these nations can be defined into two major categories: *urban* and *rural*. Throughout the rest of this document *urban communities* will be considered as:

[1]United States Dollar (USD)

1. All places with a municipality, corporation, cantonment board or notified town area committee, etc. (known as a "Statutory Town")
2. All other places which satisfied the following criteria (known as a "Census Town"):
   - A minimum population of 5,000
   - At least 75% of the male main workers engaged in non-agricultural pursuits
   - A population density of at least 400 $\frac{\text{people}}{\text{km}^2}$

Whereas *rural communities* will be defined as all other groups and areas that do not meet criteria 1 and/or 2 listed above, in accordance to the definitions given by the Indian Ministry of Home Affairs [2]. *Tribal communities* will be considered as subset of the rural population who tend to be even further isolated and have their own unique cultural identity and practices.

There are stark differences in access to quality health care when comparing rural and tribal areas of developing countries with their urban counterparts. Rural areas of developing countries tend to be poorer than the urban areas of the same nations. The World Bank reports that in 2008, 76% of the estimated 1.3 billion poor people in developing countries lived in rural areas [5]. The Oxford Poverty & Human Development Initiative of Oxford University estimates that the share of rural poor is even higher. They state that in 2014, of all of the poor across 105 countries, 85% lived in rural areas. This analysis was done using a tool called the multidimensional poverty index (MPI), an index which "reflects different deprivations individuals face simultaneously" such as health, education, and standard of living, and rates them equally along with other indicators [6]. This tool allows a broader interpretation of poverty and offers a better way to have direct comparisons between citizens of the same country and internationally. A breakdown of the total poverty percentages and rural portions is shown in Figure 2.

	Number of Countries	Total Population (thousands)	Number of MPI Poor (thousands)	Number of Rural Poor (thousands)	Number of Urban Poor (thousands)	MPI poor living in rural areas 'Rural Share' (%)
All Countries[4]	**105**	**4,001,345**	**1,433,456**	**1,214,322**	**219,134**	**84.7%**
East Asia & Pacific (excluding China)[5]	9	514,360	64,663	46,863	17,800	72.5%
Europe & Central Asia	17	233,731	8,820	5,543	3,277	62.8%
Latin America & Caribbean	15	469,739	28,697	19,953	8,744	69.5%
Middle East & North Africa	9	206,909	25,345	19,074	6,271	75.3%
South Asia	8	1,606,945	833,946	719,496	114,450	86.3%
Sub-Saharan Africa	38	789,187	469,342	402,637	66,705	85.8%
High Income Countries	9	180,474	2,643	756	1,887	28.6%

Figure 2: MPI Income Poverty by Region[2][6]

As can been seen in Figure 2 the region with the largest total amount of MPI poor is South Asia with 834 million people, 86.3% of which live in rural areas. This is reflective of India's rural-urban divide as well, as it has been determined there is an 86% rural poverty share [6].

The global population has been making a steady shift towards urbanization, as can be seen in Figure 3.

[2]This table uses the MPI estimations for 105 countries (Alkire, Conconi and Seth 2014) using 2003-2013 data (with 60 countries' data being from 2008-13). Argentina and Slovenia are excluded as their surveys do not cover rural areas; China is excluded because MPI data are from 2002. Estimates are aggregated using 2010 UN Population Statistics from UNDESA (2013). Regional definitions use the World Bank regional classification to facilitate comparison with the income poverty tables

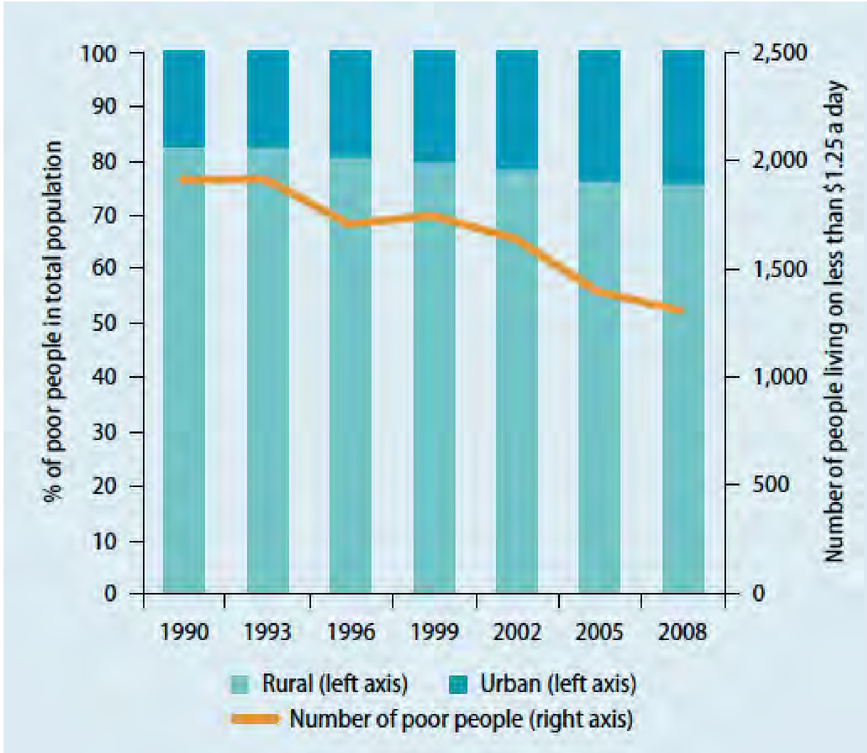

Figure 3: Rural and Urban Share of Global Poor [5]

This trend has continued year after year. However, despite this growing urbanization, the rural communities encompass the larger share of the population (and subsequently the poor) all around the world, and are in desperate need of affordable and accessible health care. In India specifically, the situation is the same. The overall percentage of the population living in urban areas increased from 2001 to 2011, but 68.86% of the population (roughly 833 million people) remain in rural areas [2]. These values can bee seen in Table 1.

	2001	**2011**
Total Indian Population	1.03 billion	1.21 billion
Urban	286 million	377 million
Percentage of Total	27.79%	31.16%
Rural	743 million	833 million
Percentage of Total	72.20%	68.86%

Table 1: Urban and Rural Population in India [2]

In order to provide adequate health care to its citizens and minimize the current short comings, developing nations must put their focus on how to best reach those who live in these rural areas. According to Peters et. al. this challenge can be broken down into four subsections which governments or other entities can target [4]:

1. *Geographic Accessibility* - the physical distance or travel time from the health service delivery point to the user.
2. *Availability* - having the right type of care, service provider, and materials available to those who need it, as well as having open hours and waiting times that meet demands of the potential patients.
3. *Financial Accessibility* - the willingness and ability of users to pay for the health services.
4. *Acceptability* - the discrepancies between how responsive health service providers are to the social and cultural expectations of individual users and communities.

These target areas are visually represented in Figure 4.

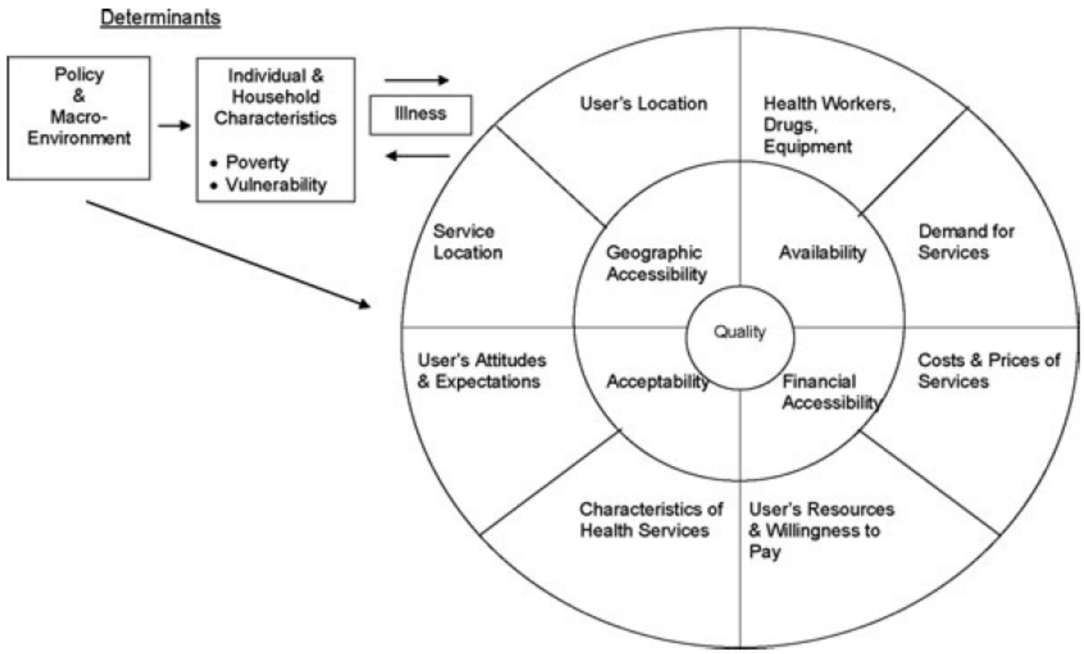

Figure 4: Target Areas for Access to Health Services [4]

In an effort address these four points, many nations have turned to the use of primary health centers (PHCs) to address and promote primary health care.

2.2 The Primary Health Care Concept

The Alma-Ata conference went on to define primary health care as:

> essential health care based on practical, scientifically sound and socially acceptable methods and technology made universally accessible to individuals and families in the community . . . It is the first level of contact of individuals, the family and community with the national health system bringing health care as close as possible to where people live and work . . . it also addresses the main health problems in the community, providing promotive, preventive, curative and rehabilitative services accordingly . . . includes at least: education concerning prevailing health problems and the methods of preventing and controlling them; promotion of food supply and proper nutrition; an adequate supply of safe water and basic sanitation; maternal and child health care, including family planning; immunization against the major infectious diseases; prevention and control of locally endemic diseases; appropriate treatment of common diseases and injuries; and provision of essential drugs

An important aspect to consider is that primary health care takes on not only the medical treatment of the patient base, but also a role of education on healthy living and recommended medical practices. This brings primary health care into the realm of both curative and preventative care.

2.2.1 Primary Health Care in India

An original concept of primary health care first set hold in India in 1946, 32 years before the Alma-Ata conference. Since then, numerous committees during both British rule and post-independence have taken on the mission of providing this service to Indians in rural and tribal areas. The work in rural India through the later half of the 20th century led to the development of the National Rural Health Mission (NRHM) in April 2005 [7].

The NRHM has enacted a three tiered rural health care system, between subcenters (SC), PHCs, and community health centers (CHC) as can be seen in Figure 5. These three tiers of the health care system cover the roughly the populations shown in Table 2.

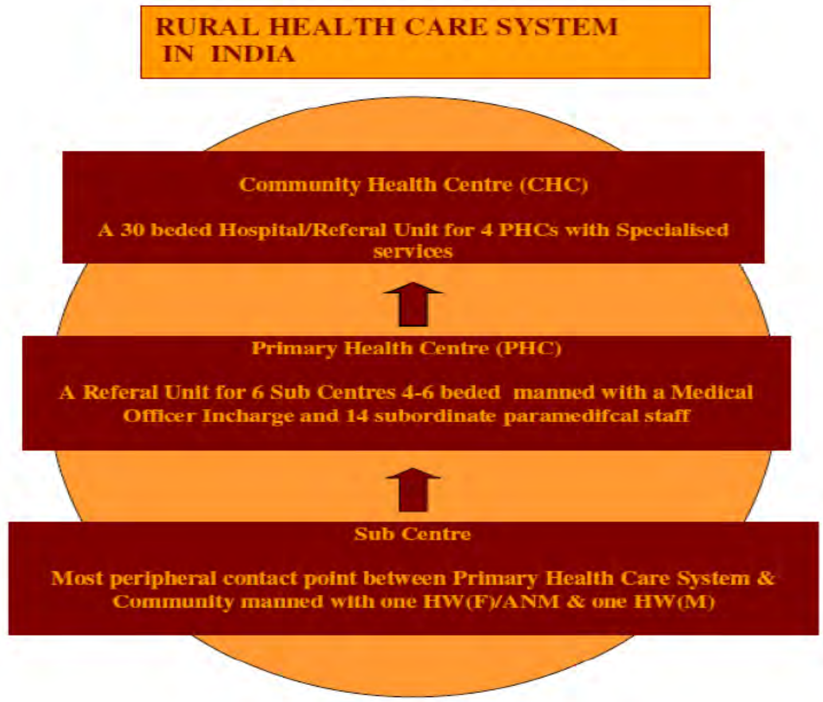

Figure 5: Tiered Rural Health Care System in India [7]

Center	**Population Averages**	
	Plain Area	Hilly/Tribal/Isolated Area
Subcenter (SC)	5,000	3,000
Primary Health Center (PHC)	30,000	20,000
Community Health Center (CHC)	120,000	80,000

Table 2: Population Averages for Tiered Rural Health Care System in India [7]

As shown, PHCs act as an intermediary between the SCs which are the smallest branch of the rural health mission, while the CHCs service a much wider area and have more specialized facilities. Therefore medical personnel in PHCs need to be able to supply a sufficient amount of health services to their patients, while still being relatively close to their patient base. In order to adequately supply the necessary care, these PHCs require a reliable supply of energy.

3 Energy Usage in Primary Health Centers

3.1 Common Energy Requirements of PHCs

The care that PHCs must give to their patient base often requires the use of some equipment or devices to help diagnose, analyze, and treat ailments. According to the International Energy Agency (IEA) the main loads that the average PHC would need to power are [8]:

1. *Lighting* - this gives the staff of a PHC the ability to carry out basic tasks, provides the possibility of health education sessions, and allows medical services all to be provided at night. Outdoor lighting of the PHC also makes them accessible and positive landmarks in the community.
2. *Vaccine Refrigeration* - as will be discussed further in Section 6, having appropriate cold storage in PHCs is a crucial requirement in order to provide the vaccinations and medicines needed to prevent and combat dangerous diseases that are prevalent in rural communities in developing countries.

3. *Sterilization* - the use of autoclaves to sterilize medical equipment is incredibly important to ensure procedures are carried out as safely as possible. This sterilization process is often very energy intensive.

4. *Medical Equipment* - various medical devices and instruments require a reliable power supply. Some common examples include:

   (a) *Microscopes* - which are often used to diagnose patients to determine the existents and type of diseases prevalent in their communities.

   (b) *Centrifuges* - are commonly used to carry out appropriate testing of samples from patients.

   (c) *Spectrophotometer* - is a device used to diagnose diseases in their early development

   (d) *Incubator* - a device used to maintain a suitable environment for a newborn baby (whether it be a premature birth or full-term).

   (e) *Other* - there are various other pieces of modern medical equipment that could be of use to a rural PHC and would require an electricity supply for their use, such as x-rays, incubators, among many others.

On top of these loads, PHCs can also have requirements to power other appliances such as ceiling fans, radios, telephones, water treatment units, water supply systems, as well as amenities for health care workers living in and around the PHCs [9].

3.2 Lack of Electricity in PHCs

However, despite the clear needs of PHCs as described in Section 3.1, electricity reliability and quality are constant issues for rural PHCs. Due to their isolated nature, it is very common that the regions that a PHC services are either completely off of the grid, or have very intermittent electricity supplies. In 2013 it was estimated that globally there are 1 billion people who are serviced by health facilities without access to electricity. In India, 46% of health facilities don't have electricity. These disconnected facilities serve an estimated 580 million people in the country [10]. Figure 6 shows a snapshot of the electrification rates, and reliability of that electricity, for health facilities in a select group of developing countries.

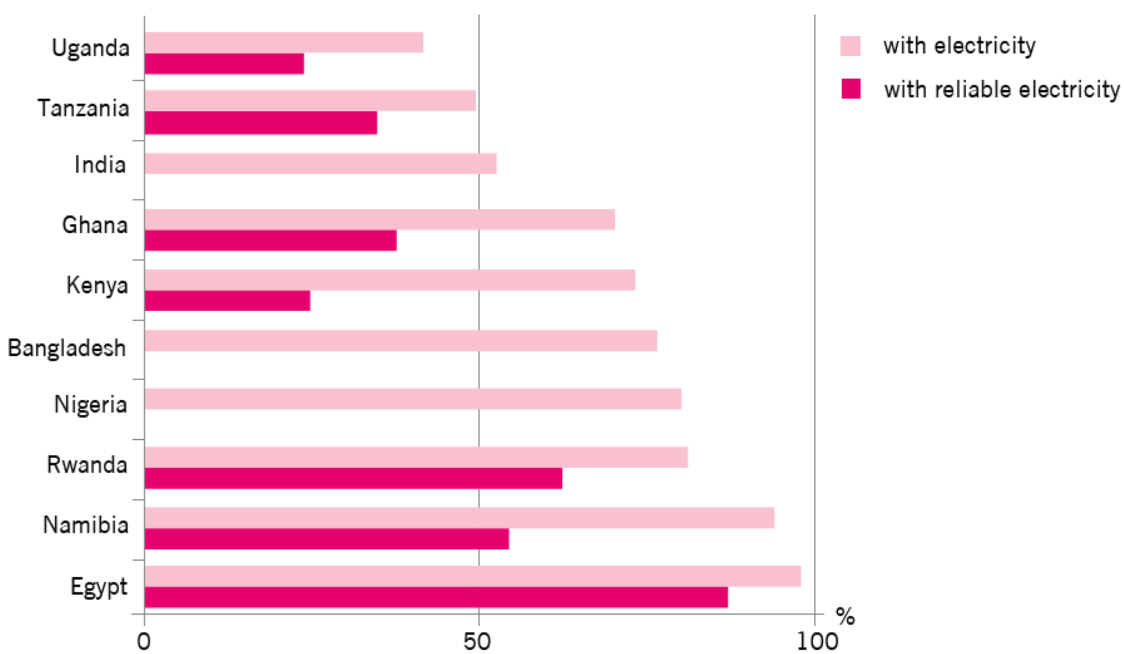

Figure 6: Electricity Access in Health Facilities in Developing Countries[3][10]

[3]There was no available data for the reliability of electricity for health centers in India, Bangladesh, or Nigeria

The facilities that are without power, or with unreliable electricity, are most often in rural areas. For example, in Uganda, only 1% of the rural health centers have grid connection [10]. This proves to be a major hurdle for PHCs in their attempts to provide the care their patients need and to perform fundamental tasks in and around the site such as documentation or basic communication.

In order to combat this prevalent issue, a common recourse for PHC operators has been to employ the use of a generator system. The generators used for this application can range in type depending on the location and availability of fuel, but diesel generator sets tend to be the most common. A major hurdle with the use of generators such as this is getting the required fuel to these remote locations, as will be discussed in Section 7. A survey by WHO of six sub-Saharan African countries revealed that less than 30% of the sites with diesel generators had them functioning properly with the required fuel on hand. However, when the fuel is available, diesel generators produce high quantities of harmful particulate matter (PM) and emit greenhouse gases [11]. An example of one of these diesel generators is show in Figure 7.

Figure 7: Diesel Generator for SRR Pura PHC, Karnataka, India

Despite these problems, these generators have often been chosen in the past due to their lower investment costs when compared to renewable electricity sources. However a study conducted by the Cooperation & Development Center (CODEV) at Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland in August 2017 has reported that fossil fuel generators such as this are no longer competitive with renewable sources when they are used in medium to large health centers, and when comparing their levelized cost of energy (LCOE)[4] [12].

3.3 Renewable Energy in Primary Health Care

19 years ago, in 1998, the National Renewable Energy Laboratory (NREL) in the United States first came to the realization that the "distribution of energy by conventional means has failed to be reliable or affordable in meeting the modest needs of rural health clinics in many developing countries" [9]. They went on to give proposals for the use of renewable energy sources to satisfy the needs of primary health centers in rural areas. Figure 8 shows an example of some of the ways a PHC could use renewables, in this case primarily through the use of solar PV technology.

[4] The concept of LCOE is explained in Section 4.3

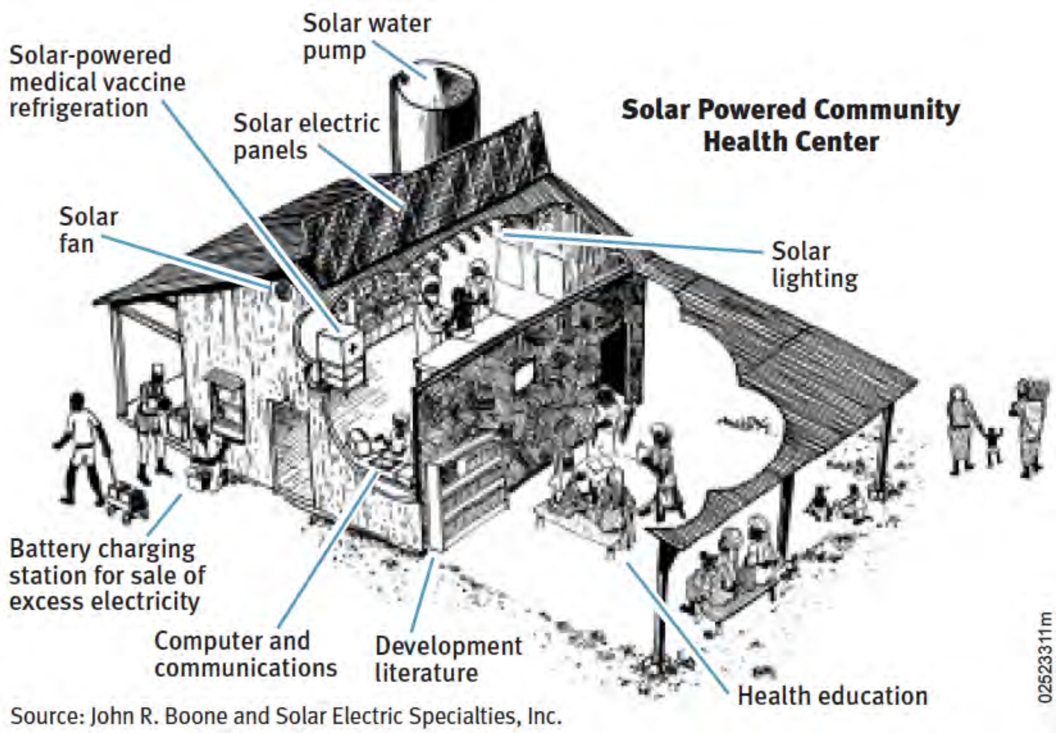

Figure 8: Solar Powered PHC Example [9]

Utilizing solar PV offers an alternative to power the activities of a PHC rather than depending on unreliable grid connected power supplies. Since the writing of that original NREL document there is still unfortunately a large disconnect between the energy needs of rural PHCs in developing countries and the ability of conventional electricity supplies to satisfy them.

However, on a positive side, since 1998 the cost of renewables and their associated products (inverters, charge controllers, batteries, etc.) have all dropped dramatically[5]. This significant drop in cost has made renewable energy alternatives not only competitive with grid connection and fossil fuel based sources, but in some cases it is now the most logical option from both a reliability and an economic standpoint (when looking at the lifetime of a system) [11].

With this fall in cost, there has been a tandem rise in health care products that are able to run on direct current (DC). Solar PV devices produce DC during their operation as is explained in Section 4.2. This provides even more incentives for PHCs to utilize solar PV which can then be connected directly to their devices.

[5]This reduction in cost over time is discussed further in Section 4.3

4 Solar Photovoltaics

In order to proceed effectively, it is necessary to establish an understanding what exactly solar photovoltaic technology is, the fundamentals of how PV devices operate, and how the technology has developed over time to reach its current state.

4.1 Introduction to Solar PV

Solar PV devices take advantage of a physical phenomenon called the *photovoltaic effect*, first discovered by Edmond Becquerel in 1839. The photovoltaic effect is a physical phenomenon where a voltage or electric current is produced between two electrodes that are attached in a system, when light is shined upon it [13].

This effect allows electricity to be produced directly from sunlight and bypasses the need for any sort of thermal conversion, working of a turbine, or any moving parts which are regularly seen in conventional power generation systems. Modern solar PV devices have a simplistic design and are able to operate with relatively little maintenance [14].

In 1954 scientists at Bell Telephone in the United States discovered that the photovoltaic effect was present in the element Silicon (Si), an abundantly available material on earth, commonly found in sand. With this discovery the modern silicon based, flat plate solar PV cell was born. Shortly after thin film technology was developed, which operates based on semiconductor materials that are micrometers (µm) thick. Due to the high cost of these early power sources, they were only being used for niche applications such as powering equipment on satellites, or for small devices such as calculators and watches. [15].

However, since that time, and especially in the past decade, the price of solar PV has dropped significantly, as will be explained in more detail in Section 4.3. As of April 2016, there was an estimated global solar PV capacity of 303 gigawatts (GW), or 1.8% of the planet's electricity demand - a massive rise from its former negligible status on the world stage as is shown in Figure 9. [16].

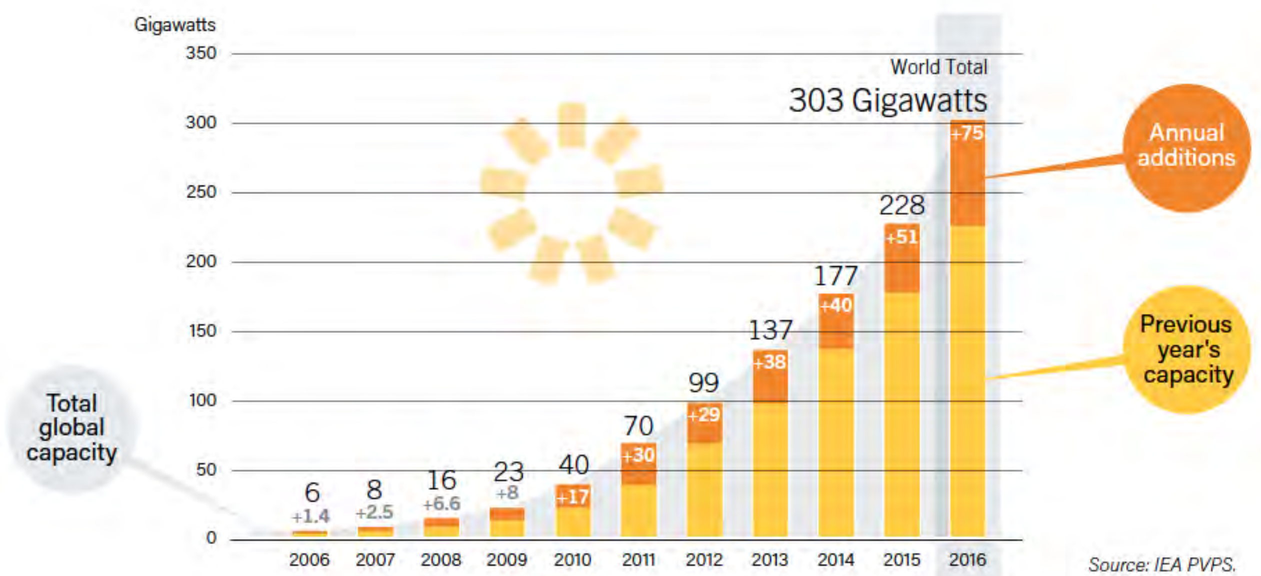

Figure 9: Global Capacity of Solar PV & Annual Additions [17]

As can be seen, the overall capacity has been increasing year after year, along with the annual addition to the global capacity[6].

[6]with the exception of 2011 to 2012 where there was a 1GW decrease in annual additions of solar PV capacity

4.2 How Solar PV Technology Works

As mentioned in Section 4.1 solar PV devices operate on the principle of the photoelectric effect and are most often Si based devices. Si is what is known as a *semiconductor*, meaning that its electrical conductivity falls between that of an insulator and a conductor. It is also an element with four valence electrons (i.e. four electrons in its outermost band). Si will always strive to completely fill this outer band to the maximum amount of eight electrons. Taking this into consideration, during the solar cell manufacturing process, another element (the dopant) is added to the Si in a process called *doping* [18].

The dopant Phosphorous (P), which naturally has five electrons in its valence band, can be added to one half of the Si. This results in an excess amount on electrons in that material, and it is referred to as a Negative-type (N-type) material. Conversely, on the other half, Boron (B), an element with three electrons in its valence band, can be added to the other half[7]. This results in a lack of electrons in that material (also known as an excess of *holes*), and it is referred to as a Positive-type (P-type) material [18].

When the P-type material and N-type material are in contact with one another, it creates what is known as a *P-N junction*. When the junction is formed, electrons from the N-type material move to fill the holes in the P-type material. This reaches an equilibrium and an electric field is formed, forming a diode which forces electrons from the P-type to the N-type. This is known as the depletion zone of the semiconductor as can be seen in Figure 10. The force from the electric field keeps electrons from flowing from the N-type to the P-type [19].

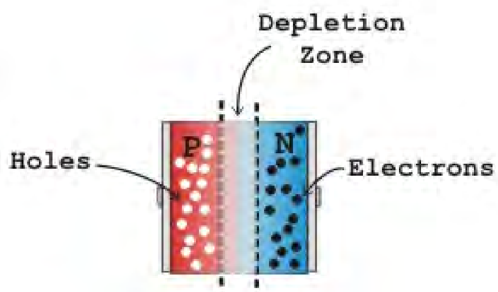

Figure 10: P-N Junction & Depletion Zone [19]

However this electric field can be overcome if an electron in the N-type is excited in some way. This excitation can happen if a photon of solar radiation of a certain wavelength hits the N-type, giving an electron enough energy to jump the depletion zone and move to the P-type material. This creates a hole in the N-type, and the combination is known as an electron-hole pair. If a conductor, such as a wire, is place to connect the P-type to the N-type material, the electron will travel through it, and back to the N-type, creating electricity which can power a load, as can be seen in Figure 11.

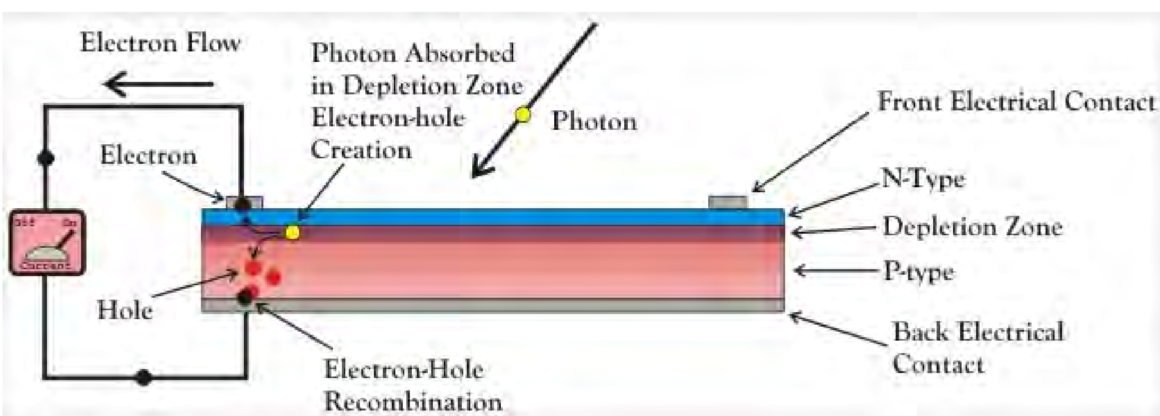

Figure 11: A Photovoltaic Cell [20]

[7]Dopants can also be differing elements, but phosphorous and boron are commonly used

4.2.1 Analyzing the Solar Resource

When evaluating the possible installation of a solar PV system, it is critical to first determine the quality of the solar resource in the location. Irradiance (the radiant flux of sunlight received by a surface) can be can be broken down into three categories [21]:

1. Direct Normal Irradiance (DNI) - the amount of solar irradiance, when the surface if perpendicular to the sun's position in the sky.
2. Direct Horizontal Irradiance (DHI) - the amount of solar radiation that hits a surface per unit area that does not come from a direct path from the sun.
3. Global Horizontal Irradiance (GHI) - the total amount of solar irradiance that hits a surface, defined in Equation 1 as:

$$\text{GHI} = \text{DNI} \times \theta + \text{GHI} \tag{1}$$

Where:

- θ is the solar zenith angle, the angle between the direction of the sun and completely overhead the location of interest.
- and the other variables are defined as listed above.

These forms of irradiance can be visualized in Figure 12.

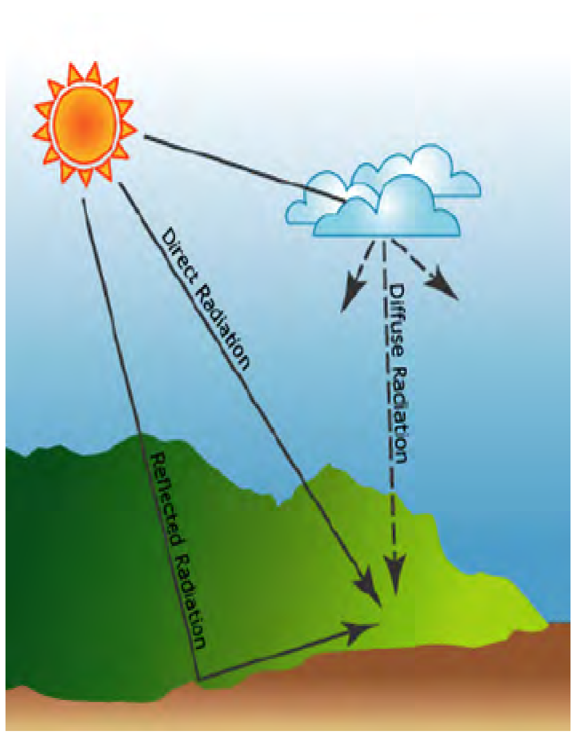

Figure 12: Solar Irradiance [21]

This principles and definitions will be used in Section 7.3.1 when analyzing the feasibility of a PV system in the field.

4.3 Financial Aspects of Solar PV

As mentioned in Section 4.1, the price of solar PV has dropped significantly since its modern inception in the middle of the 20th century. PV module pricing has gone from $300\frac{\text{USD}}{\text{W}}$[8] in 1956, to $50\frac{\text{USD}}{\text{W}}$ in the 1970s, to $10\frac{\text{USD}}{\text{W}}$ in the 1990s, and now roughly $0.40\frac{\text{USD}}{\text{W}}$ today [16].

This falling price is due to a decrease in manufacturing costs as processes became more efficient with mass production and increased competition between solar PV manufacturers. Solar cells have also become more efficient and able to produce more power per unit area over time. Therefore, the price per unit power has also decreased. There has also been some government motivation in the sector, in the form of tax credits in some countries, which has lowered the price even further, boosting demand, and continuing the cycle or lowering manufacturing cost and increased power production efficiency of the panels [22].

This decline in price can be visualized in Figure 13.

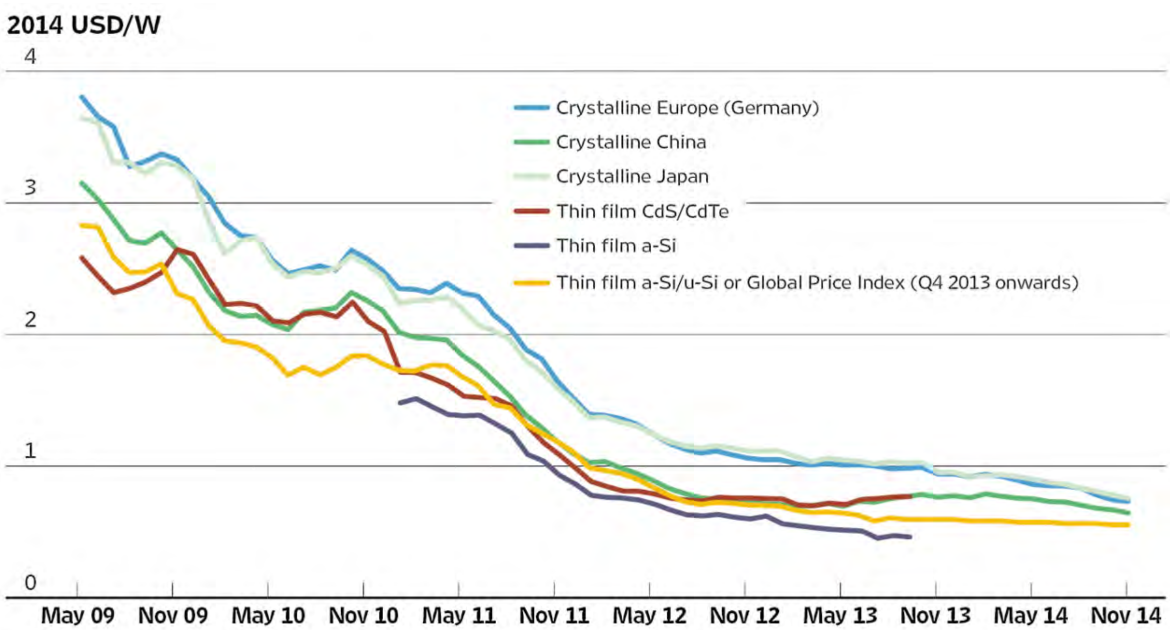

Figure 13: Cost of Solar PV Over Time[9][23]

This falling price per W is a clear indicator of solar PV's rising competitiveness in the energy market, but it is also important to compare the technology with other energy sources being used. This can be done by means of comparing the levelized cost of energy (LCOE) which is defined in Equation 2[24].

$$\text{LCOE} = \frac{\text{Total Life Cycle Costs}}{\text{Total Lifetime Energy Production}} \tag{2}$$

The LCOEs of different renewable energy technologies compared with those of fossil fuels is shown in Figure 14

[8]USD per Watt (W)

[9]This chart is of the average monthly solar PV module prices by technology and manufacturing country sold in Europe from 2009 to 2014

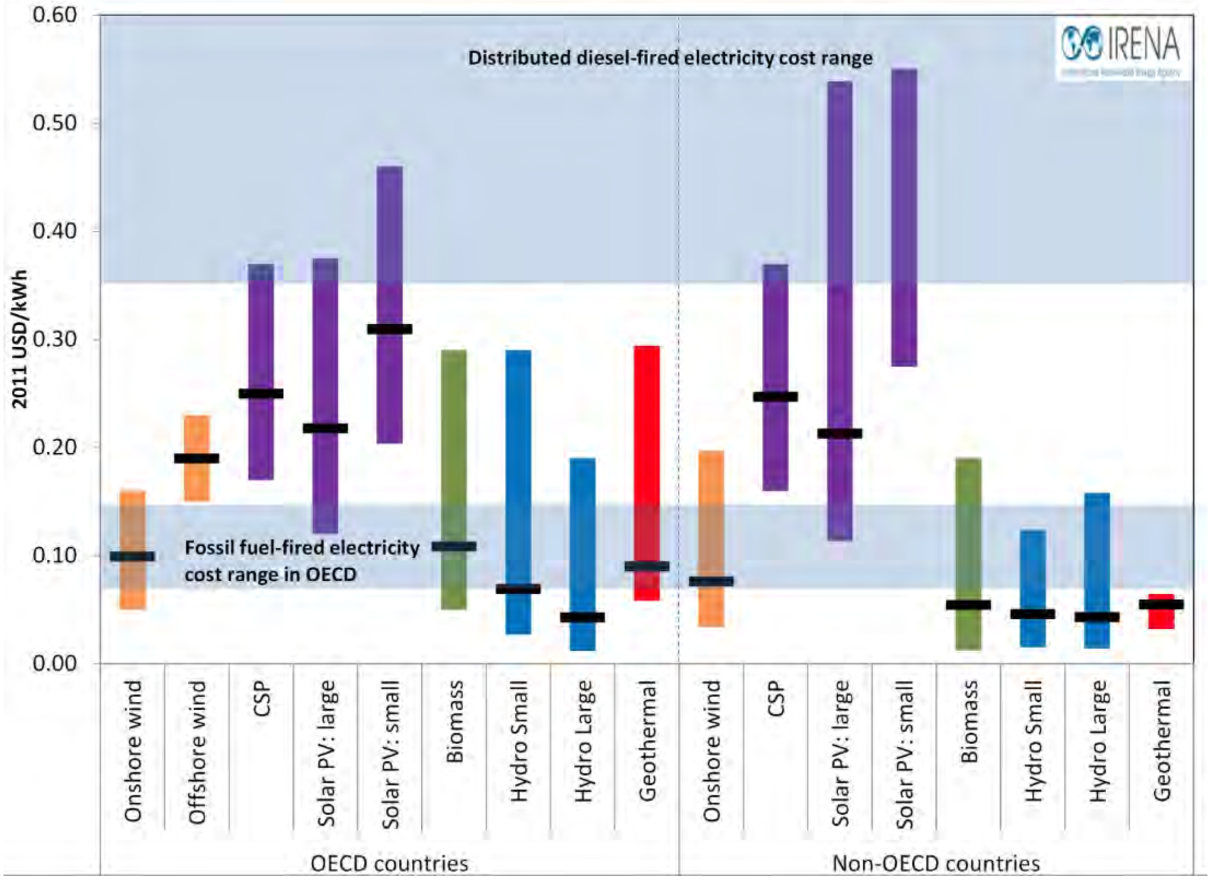

Figure 14: LCOE for Different Energy Technologies [25]

Although the LCOE on average is still slightly higher than most fossil fuels, the LCOE of solar PV has halved between 2010 and 2014 and continues to drop as time goes on [26]. With this continuing drop in the cost of solar PV technology, it has opened the door for its utilization in many fields, including rural health care.

5 Solar Powering Primary Health Centers in India

As stated in Section 3.3 the use of solar PV technology provides a plethora of interesting opportunities to be used in rural PHCs. This section will take a look into the use of this technology which has been utilized in six PHCs in an effort to tackle the constant issue of electricity unreliability in rural PHCs. The implementation of these systems was carried out in coordination with:

- SELCO Solar Pvt. Ltd, or SELCO India - a social enterprise established in 1995, which provides sustainable energy solutions and services to under-served households and businesses. SELCO originally stood for Solar Electric Light Company [27].
- The SELCO Foundation - which branched off of the mission of SELCO India and was founded in 2010 as an open source, not for profit, charitable trust. The non-governmental organization (NGO) works with decentralized energy solutions "to bridge the gap between high risk innovations and eco-system development for under-served communities". These projects are field tested, and if successful, replicated in other areas to help communities in need [28].
- Karuna Trust - an NGO specializing in implementing innovative solutions to improve the health, livelihood, and development of rural and tribal regions in India since 1986 [29].

The six PHCs are all within the south Indian state of Karnataka. Their locations are marked by medical crosses and shown in Figure 15, they are now all operated by Karuna Trust.

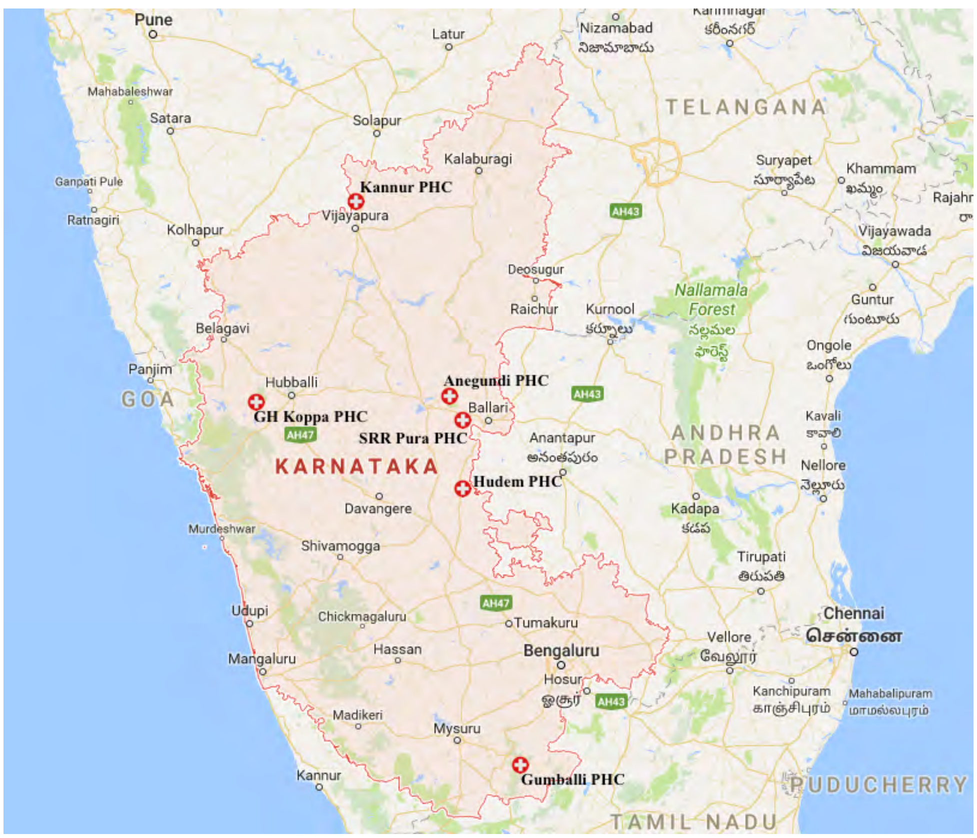

Figure 15: Karnataka PHC Locations [30]

Background information on each PHC, an assessment of the services they provide, how many citizens they reach, their electricity usage and reliability profiles, as well as details of the solar systems that have since been installed will all be presented in Sections 5.1 to 5.6.

5.1 Gumballi PHC

The Gumballi PHC (shown in Figure 16) in Chamarajanagar district was originally founded by the Karuna Trust in 1996 when the Government of Karnataka entrusted the existing health center to the NGO. Since then it has served as a model for other PHCs throughout the country. The Gumballi PHC provides health services to a population of 22,144 in the area, 60% of which are of the Soliga tribe from the BR Hills. There 18 members of the staff working at the PHC, and there are 5 SCs underneath its scope [31, 32].

Figure 16: Gumballi PHC

The Gumballi PHC has an outpatient department (OPD)[10], an inpatient department (IPD)[11], an eye hospital which offers cataract operations every Thursday, dental care (shown in Figure 17), a labor room, operation theater (OT), pharmacy, laboratory, mental health facilities, medical record & office rooms, as well as patient wards. Some of these services are beyond the scope of a typical PHC, but as an original pilot project it was a testing ground to see which services could be given in a rural setting such as this [32].

Figure 17: Gumballi PHC Dental Room

[10]The OPD is the department that treats all visitors who are not checked into the PHC to spend significant time getting treatment there

[11]The IPD the department that treats all visitors who have been checked in and will receive more long term care

Information on the number of patients seen between 2010 and 2011 is shown in Table 3. Over this time period there were no emergency visits to the PHC.

	IPD		OPD	
	Male	Female	Male	Female
April 2010	6	0	573	501
May 2010	47	50	758	714
June 2010	12	25	870	793
July 2010	2	5	893	810
August 2010	1	4	957	817
September 2010	1	8	836	700
October 2010	3	6	673	609
November 2010	0	3	763	687
December 2010	0	7	739	700
January 2011	1	5	712	640
February 2011	1	12	653	628
March 2011	2	14	0	0
Total	**76**	**184**	**8,427**	**7,599**

Table 3: Gumballi PHC 2010-2011 Patient Details [32]

As could be imagined, the amount of patients in the OPD every month is much higher than IPD. This will be a reoccurring theme through the analysis of the other PHCs.

The Gumballi PHC provides medical recourse for the community it services, however, there is unreliability with the power supply in the region. Power cuts reportedly last for hours, causing patients to wait to receive the proper treatment needed and appointments to be cancelled. This can be a large problem for those seeking medical attention, because a trip to the PHC would often mean taking a day off of work, and therefore losing the crucial wages they could have otherwise earned. A diesel generator served as a backup for these situations, but since these power outages were so frequent, the cost of diesel added a significant amount to the operating costs of the PHC [33].

In an effort to help with this ever present issue, the SELCO Foundation & SELCO India helped design and install a solar PV system for the PHC.

5.1.1 PV System Details

To combat this issue of intermittent power supply in the PHC, a 3.2 kilowatt (kW) solar PV system with 1,080 Ampere-hour (Ah) lead acid battery bank were installed. The loads connected to this system are summarized in Table 4

Table 4: Gumballi PHC Load Details

Section of PHC	Equipment	Quantity	Estimated Load [W]
Entrance	Light Emitting Diode (LED) Tube Light	1	10
Veranda	LED Tube Light	1	5
Toilet	LED Tube Light	1	5
Dental Unit	Compressor	1	850
	X-ray	1	1,150
	Dental Chair	1	295

continued on next page

Table 4 – continued from previous page

Section of PHC	Equipment	Quantity	Estimated Load [W]
	LED Tube Light	1	18
Consultation Room	LED Tube Light	1	18
Medical Records Room	LED Tube Light	1	18
	Computer	1	120
Pharmacy	LED Tube Light	1	18
	Vestfrost Deep Freezer	1	130
	Vestfrost ice Lined Refrigerator	1	120
Dressing & Injection Room	LED Tube Light	1	18
Laboratory	LED Tube Light	1	18
	Centrifuge	1	
	Digital Microscope	1	5
	Digital Photo Colorimeter	1	5
Labor Room	LED Tube Light	1	18
	Suction Machine	1	
Eye Surgery Ward	Surgery Equipment	1	25
Eye Clinic Room	Slit Lamp	1	Altogether: 120
	Keratometer	1	
	3nerthra	1	
	Biometer	1	
	LED Tube Light	1	18

Not all of the loads listed in Table 4 would be operating at the same time, and some of them would only be active for very short durations, for instance the x-ray machine in the dental office will only be on for fractions of a second.

The solar array provides supplemental power to the loads of the PHC, along with the main supply from the grid. If and when the grid is unable to provide the required power, the demand from the connected loads can be met by the PV system.

Since the installation of the solar PV system, there has been a decline in the energy usage from the grid connection in the PHC, and therefore also a reduction in the monthly electricity bill as can be seen in Figure 18.

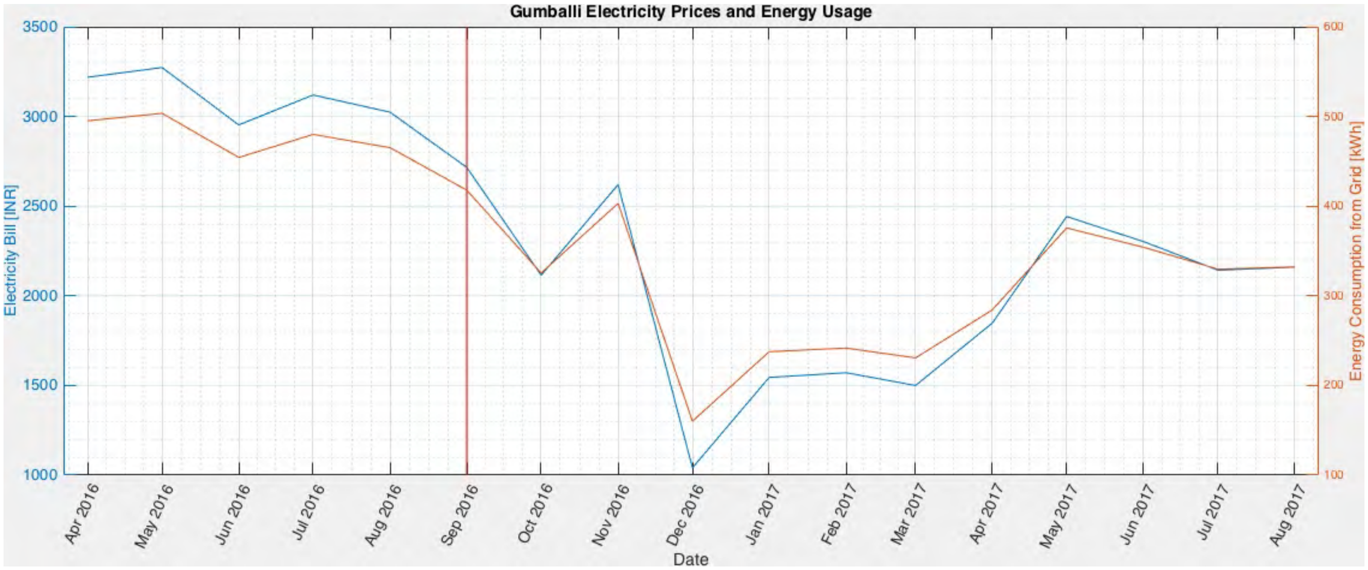

Figure 18: Gumballi PHC Monthly Electricity Bills and Energy Usage

The date of installation of the solar system is marked by the vertical red line. As can be seen, since the installation date, the usage and cost have been lower overall. There are some months of higher usage, most notably after April 2017. This may be due to the start of the monsoon season in the region, resulting in a lack of power generation from the PV installation.

From the sampled data, there was an average monthly electricity bill cost of ₹[12]3,051 before the system was installed, and an average of ₹1,935 per month after the solar system was in place, resulting in an average monthly savings of ₹1,116. More data will be needed throughout the year, with differing levels of solar irradiation, to determine if this average monthly savings will be higher or lower.

5.2 GH Koppa PHC

Galagihulukoppa, known by its abbreviated name: GH Koppa, is a PHC located in the district of Dharwad in northern Karnataka, India. It services a population of 30,209 individuals and had 5 SCs designated underneath it. It is equipped with an IPD, OPD, injection room, labor room, as well as other office spaces and congregation areas [31].

Information on the number of patients seen between 2010 and 2011 is shown in Table 5. Over this time period there were no emergency visits to the PHC.

[12]₹is the symbol for the Indian rupee (INR)

	IPD		OPD	
	Male	Female	Male	Female
April 2010	20	63	182	234
May 2010	35	47	208	369
June 2010	40	7	348	293
July 2010	35	78	127	240
August 2010	78	73	432	582
September 2010	30	43	375	376
October 2010	18	23	292	361
November 2010	13	30	471	297
December 2010	8	11	345	396
January 2011	12	12	393	429
February 2011	12	20	218	354
March 2011	20	34	166	327
Total	**322**	**441**	**3,557**	**4,258**

Table 5: GH Koppa PHC 2010-2011 Patient Details [32]

Throughout this time frame more women were treated in both the IPD and OPD. The total recorded population for this time period was 28,214, therefore it has been assumed that the average number of patients in all sectors has increased with the population [32]

Like most PHCs in rural India, sporadic electricity supply is a concern at GH Koppa. Grid connected reliability data was collected for this PHC between March 25$^{\text{th}}$ and June 2$^{\text{nd}}$ 2017. The amount and type of interruptions to the electricity supply are shown in Table 6.

Interruption Pattern	Number of Interruptions	Duration (minutes)	Duration (hours)
Short Interruptions	**165**	**1,953**	**32.55**
< 15 Minutes	126	774	12.90
15 - 60 Minutes	39	1,179	19.65
Long Interruptions	**97**	**20,147**	**335.78**
1 - 3 Hours	65	7,895	131.58
> 3 Hours	32	12,252	204.2
Total	**262**	**22,100**	**368.33**

Table 6: GH Koppa PHC Grid Interruptions Details (March 25$^{\text{th}}$ - June 2nd 2017) [34]

GH Koppa has had more instances of short power cuts that last less than 15 minutes, however the total time lost to longer interruptions is much higher. These power outages are represented in Figure 19.

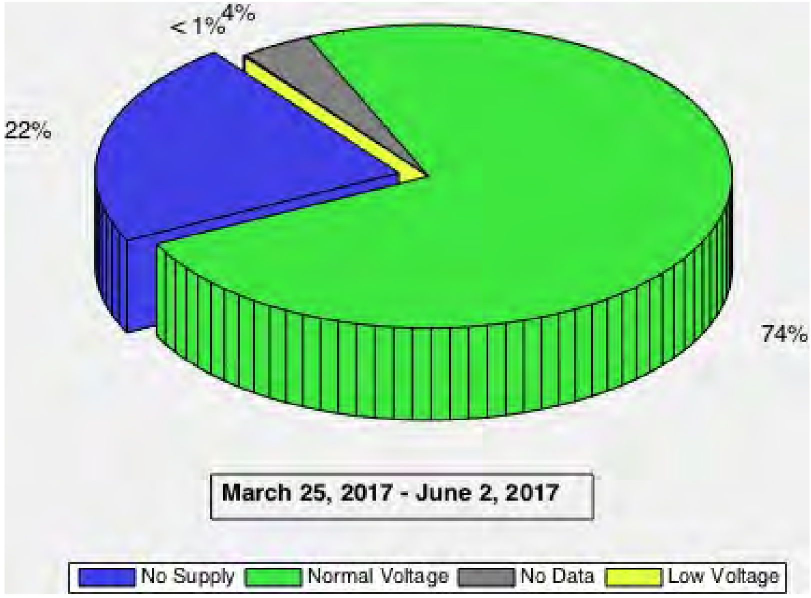

Figure 19: GH Koppa PHC Electricity Reliability Data[13][34]

As can be seen there was an average lack of supply for 22% of the time over the 70 day period, roughly 15.4 days without power. This case very clearly illustrates the situations of intermittent power supply in rural PHCs as described in Section 3.2. Situations such as this leave patients playing a lottery of sorts, hoping there will be power to provide the care they need when they make their way to the PHC.

5.2.1 PV System Details

In response, the SELCO Foundation has installed a 2.65 kW solar PV system with 1,600 Ah of lead acid battery storage capacity to help power the functions of the PHC.

The loads connected to this system are summarized in Table 7

Table 7: GH Koppa PHC Load Details

Section of PHC	Equipment	Quantity	Estimated Load [W]
Meeting Hall	Deep Freezer	1	120
Storage Room	KENT Purifier	1	60
Dressing Room	LED Tube Light	1	18
Pathway	LED Tube Light	1	18
Labor Room	Baby Warmer	1	750
	LED Tube Light	1	18
	Ceiling Fan	1	75
	Suction System	1	230
Injection Room	LED Tube Light	1	18
	Ceiling Fan	1	75
IPD	LED Tube Light	1	18
	Ceiling Fan	1	75
	Nebulizer	1	53
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75

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[13]*Normal Voltage* is classified between $210V$ & $270V$. *Low Voltage* is defined as being below $210V$ but greater than $0V$. Occasionally there were *No Data* readings due to technical issues.

Table 7 – continued from previous page

Section of PHC	Equipment	Quantity	Estimated Load [W]
	Computer	1	120
	Printer	1	360
Main Hall	LED Tube Light	1	18
	Ceiling Fan	1	75
Pharmacy	LED Tube Light	1	18
	Ceiling Fan	1	75

As stated for Gumballi PHC, not all of the loads listed in Table 7 would be operating at the same time, and some of them would only be active for very short durations.

The monthly electricity usage from the grid, and the associated electricity bills can be seen in Figure 20

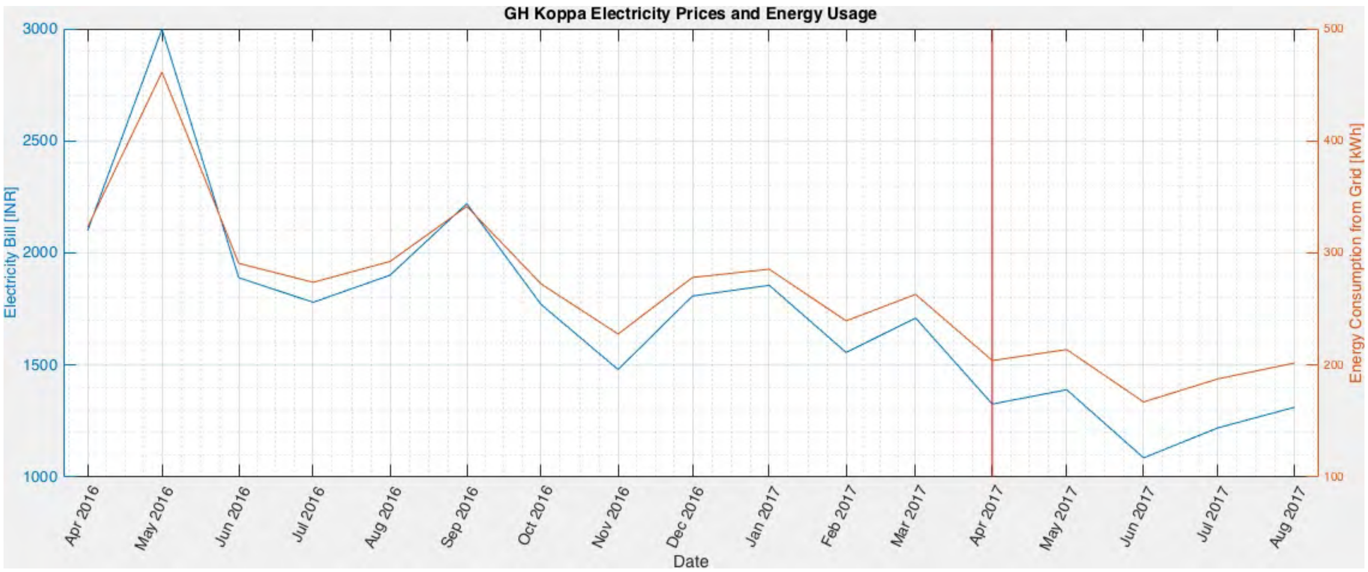

Figure 20: GH Koppa PHC Monthly Electricity Bills and Energy Usage

The vertical red line signifies the installation of the 2.65 kW solar system. As can be seen, there had been a general trend of decreasing energy usage throughout the year, culminating in an overall drop in usage of grid supplied electricity since the installation date. There is a slight increase towards July, which may be attributed to the onset of the monsoon season in Karnataka. Increasing rain and cloud cover would result in less electricity production from the solar system, and therefore more requirement from the convention grid source.

From the sampled data, there was an average monthly electricity bill cost of ₹1,877 before the system was installed, and an average of ₹1,252 per month after the solar system was in place, resulting in an average monthly savings of ₹625. More data will be needed over time to determine if this average monthly savings will be higher or lower.

5.3 Kannur PHC

Kannur PHC is located in northern Karnataka in the district of Bijapur, near Vijayapura as can be seen in Figure 15. 66,242 people and 11 SCs are under its jurisdiction. It is equipped with an IPD, OPD, injection room, labor room, office spaces, and a laboratory [31, 32].

	IPD		OPD		Emergency	
	Male	Female	Male	Female	Male	Female
April 2010	158	267	1,164	1,161	15	6
May 2010	122	236	1,026	1,186	3	2
June 2010	84	123	1,139	1,206	24	16
July 2010	99	114	1,692	2,173	10	4
August 2010	92	138	1,590	1,696	16	10
September 2010	66	94	1,590	1,696	25	16
October 2010	33	60	1,332	1,097	20	10
November 2010	12	53	1,042	961	10	4
December 2010	12	41	1,001	1,027	10	16
January 2011	49	21	1,035	886	14	10
February 2011	16	62	657	729	10	6
March 2011	30	72	606	536	12	10
Total	**778**	**1,336**	**13,927**	**14,453**	**169**	**110**

Table 8: Kannur PHC 2010-2011 Patient Details [32]

Over the course of this time Kannur PHC saw more females in both the IPD and OPD, however there were more men visiting for emergencies. Over this time period, roughly 43% of the serviced population came in to the Kannur PHC for OPD visits, a very large portion.

Although Kannur PHC services a large number of inhabitants in the area, it is as well a victim of frequent power cuts and unreliable electricity. The types of interruptions in their electricity connection, as well as a graphical representation of the amount of time the supply of electricity is within normal bounds or not, are shown in Table 9 and Figure 21 respectively.

Interruption Pattern	Number of Interruptions	Duration (minutes)	Duration (hours)
Short Interruptions	**403**	**6,116**	**101.93**
< 15 Minutes	261	1,478	24.63
15 - 60 Minutes	142	4,638	77.30
Long Interruptions	**319**	**45,132**	**752.20**
1 - 3 Hours	267	29,232	487.20
> 3 Hours	52	15,900	265.00
Total	**722**	**51,248**	**854.13**

Table 9: Kannur PHC Grid Interruptions Details (March 25th - September 5th 2017) [35]

As Table 9 shows Kannur PHC suffered from over 700 interruptions during the timespan, the majority of them being short interruptions. In total the PHC was lacking power for 35.6 days. The percentage shares of the type of power the Kannur PHC was receiving can be seen in Figure 21

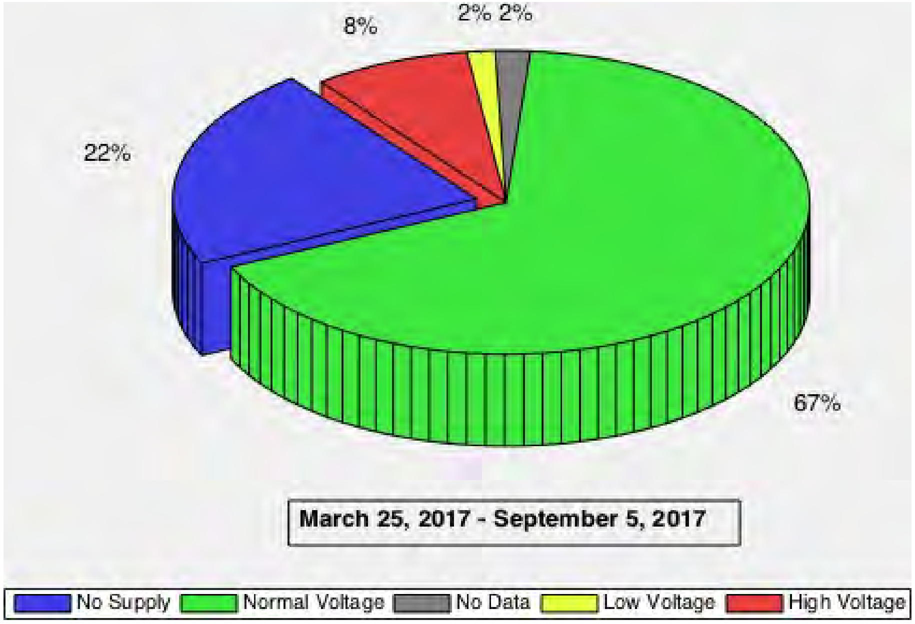

Figure 21: Kannur PHC Electricity Reliability Data[14][35]

Over the 165 day period, the PHC had a normal supply of electricity for only 67% of the time. This would be a massive hurdle for the operations of Kannur PHC considering the large population base they serve and the amount of patients they receive.

5.3.1 PV System Details

As with the other PHCs, a solar PV system has since been installed to try and alleviate this issue. A 2.65 kW system with 1,600 Ah of lead acid battery storage was put in place. The loads connected to this system are very similar to the loads for GH Koppa and are summarized in Table 10

Table 10: Kannur PHC Load Details

Section of PHC	Equipment	Quantity	Estimated Load [W]
Meeting Hall	Deep Freezer	1	120
Storage Room	KENT Purifier	1	60
Pathway	LED Tube Light	1	75
Dressing Room	LED Tube Light	1	18
Labor Room	Baby Warmer	1	750
	LED Tube Light	1	18
	Ceiling Fan	1	75
	Suction System	1	230
Injection Room	LED Tube Light	1	18
	Ceiling Fan	1	75
IPD	LED Tube Light	1	18
	Ceiling Fan	1	75
	Nebulizer	1	53
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Computer	1	120

continued on next page

[14] *Normal Voltage* is classified between 210V & 270V. *High Voltage* and *Low Voltage* are defined outside of those boundaries accordingly. Occasionally there were *No Data* readings due to technical issues.

Table 10 – continued from previous page

Section of PHC	Equipment	Quantity	Estimated Load [W]
	Printer	1	360
Main Hall	LED Tube Light	1	75
	Ceiling Fan	1	75
Pharmacy	LED Tube Light	1	18
	Ceiling Fan	1	75

The electricity usages from the grid and the electricity bill for the PHC before and after the installation of this 2.65 kW system, can be seen in Figure 22.

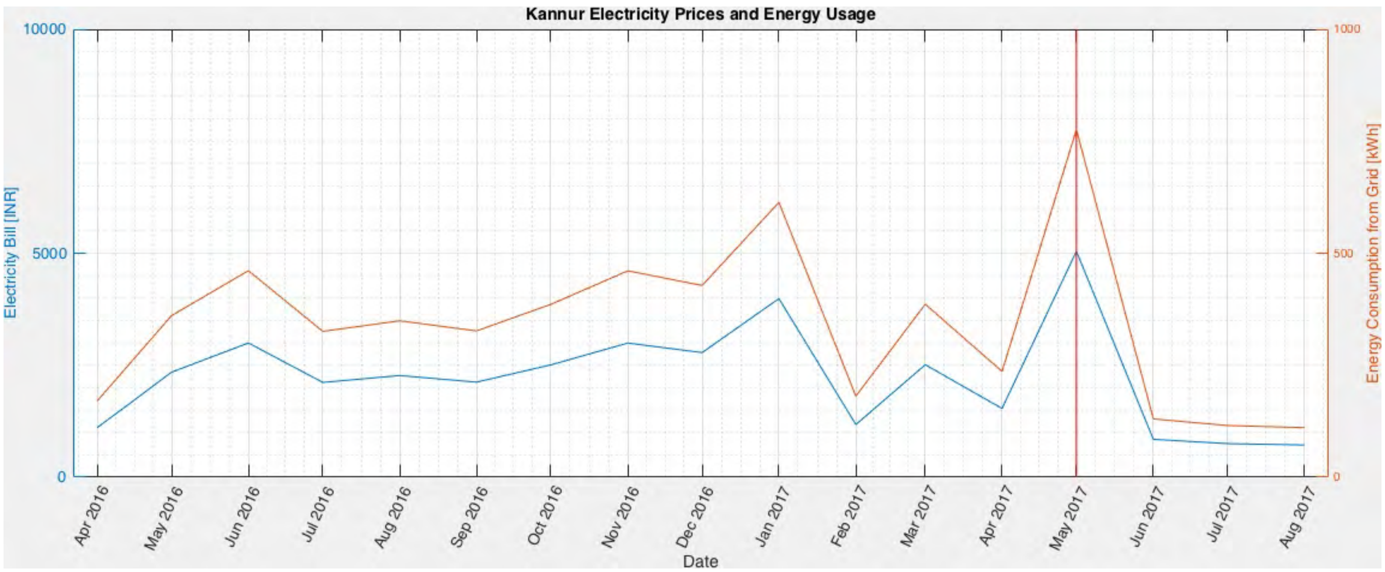

Figure 22: Kannur PHC Monthly Electricity Bills and Energy Usage

The installation date is demarcated by the vertical red line. Before the installation of the system the average monthly electricity bill was ₹2,536, and afterwards this average dropped ₹1,764 to ₹772. The system is very new and only a small data set was available to see the effects after the system has been installed, however it is still a positive indicator that there can be long term savings with the new installation in place.

5.4 Anegundi PHC

The Anegundi PHC in Koppal district services 28,336 citizens and lies across the river from the UNESCO World Heritage Site of Hampi in northern Karnataka. Anegundi has five SCs which fall under its umbrella of care [31]. The entrance to the OPD wing of the PHC can be seen in Figure 23.

Figure 23: Anegundi PHC

	IPD		OPD		Emergency	
	Male	Female	Male	Female	Male	Female
April 2010	12	23	629	481	0	0
May 2010	14	13	601	600	0	2
June 2010	12	20	641	604	0	0
July 2010	20	22	804	722	1	1
August 2010	10	13	671	600	4	3
September 2010	20	30	685	650	2	1
October 2010	3	23	537	499	2	1
November 2010	7	18	588	503	2	0
December 2010	8	18	647	590	1	0
January 2011	17	19	654	663	1	1
February 2011	14	33	662	619	3	3
March 2011	24	14	520	515	3	2
Total	**161**	**246**	**7,639**	**7,046**	**19**	**14**

Table 11: Anegundi PHC 2010-2011 Patient Details [32]

Anegundi is a smaller PHC is comparison to others, and the patients it saw over the period of April 2010 to March 2011 reflects this. As the others, the majority of its services were in the OPD, although there was a relatively high number of emergency visits to the PHC throughout the year.

As can be imagined Anegundi PHC is no exception to the issues of power cuts and shortages during its operation, although the situation does not seem to be as dire as in other PHCs. The types and durations of these outages can be seen in Table 12.

Interruption Pattern	Number of Interruptions	Duration (minutes)	Duration (hours)
Short Interruptions	**595**	**8,042**	**134.03**
< 15 Minutes	419	2,222	37.03
15 - 60 Minutes	176	5,820	97.00
Long Interruptions	**101**	**15,537**	**258.95**
1 - 3 Hours	81	8,254	137.57
> 3 Hours	20	7,283	121.38
Total	**696**	**23,579**	**392.98**

Table 12: Anegundi PHC Grid Interruptions Details (March 4th - August 25th 2017) [36]

Luckily for the residents of Anegundi, the PHC has had fewer interruptions over roughly the same time span as the other PHCs presented. This can be seen more clearly in Figure 24.

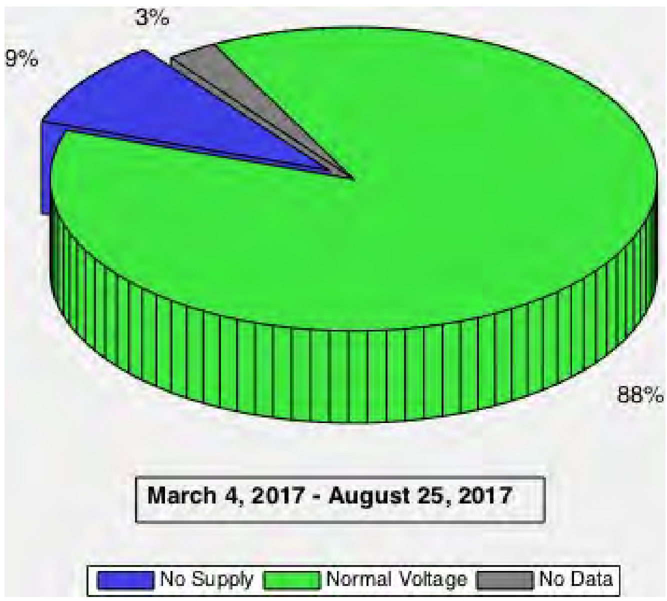

Figure 24: Anegundi PHC Electricity Reliability Data[15][36]

As can be seen, 88% of the time Anegundi PHC was being supplied with the normal voltage it required. This is a rather high value in comparison to the other PHCs, however it still poses problems for the operation of the PHC.

5.4.1 PV System Details

Similarly to the other PHCs 2.65 kW system with 1,600 Ah of lead acid battery storage was put in place. This roof mounted solar system can be seen in Figure 26.

[15] *Normal Voltage* is classified between 210V & 270V. *High Voltage* and *Low Voltage* are defined outside of those boundaries accordingly. Occasionally there were *No Data* readings due to technical issues.

Figure 25: Anegundi PHC PV System

The loads connected to this system are summarized in Table 13

Table 13: Anegundi PHC Load Details

Section of PHC	Equipment	Quantity	Estimated Load [W]
Pharmacy	LED Tube Light	1	18
Senior Health Visitor	LED Tube Light	1	18
Refractionist Room	Deep Freezer	1	120
Toilet	LED Tube Light	2	18
Medicine Storage	LED Tube Light	1	18
Pathway	LED Tube Light	3	18
Dressing Room	LED Tube Light	1	18
Medical Officer Room	LED Tube Light	2	18
	Ceiling Fan	1	75
IPD	LED Tube Light	2	18
	Ceiling Fan	3	75
	Nebulizer	1	50
Labor Room	Baby Warmer	1	750
	LED Tube Light	2	18
	Ceiling Fan	3	75
	Suction Machine	1	250
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Computer	1	120
	Printer	1	360
Lab	LG Refrigerator	1	100
	Centrifuge	1	120

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Table 13 – continued from previous page

Section of PHC	Equipment	Quantity	Estimated Load [W]
	LED Tube Light	1	18
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Water Purifier	1	50

This system has led to a decrease in the electricity demand from the grid, which is pictured in Figure 26.

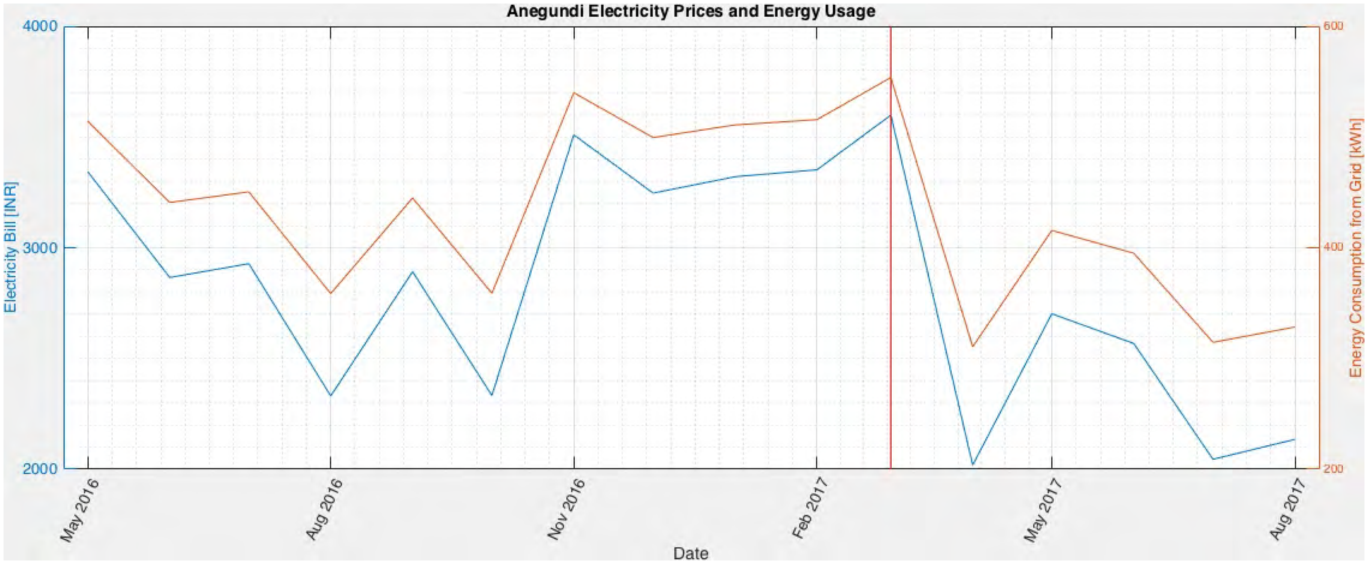

Figure 26: Anegundi PHC Monthly Electricity Bills and Energy Usage

After the installation of the system (dictated by the vertical red line), there is an overall drop in the usage and subsequent monthly bill. The monthly average before the installation was ₹3,066, while that average dropped ₹772 to ₹2,294 after the system was installed. Of course with more time and more data the longer savings that this system brings to the PHC will be able to be determined.

5.5 Hudem PHC

Hudem PHC is located in the Bellary district, between Anegundi and Bangalore. As of March 2016 it served 45,262 people with six SCs under it [31, 32].

A snapshot of the number and types of patients it saw from 2010 to 2011 can be seen in Table 14

	IPD		OPD		Emergency	
	Male	Female	Male	Female	Male	Female
April 2010	26	37	600	795	0	1
May 2010	24	34	350	508	0	8
June 2010	7	14	462	500	1	6
July 2010	20	22	804	722	1	1
August 2010	24	28	350	478	0	3
September 2010	20	34	380	447	11	1
October 2010	17	46	400	427	0	2
November 2010	22	26	450	367	5	1
December 2010	12	25	348	481	0	0
January 2011	11	30	350	369	0	7
February 2011	11	31	476	347	0	2
March 2011	13	29	430	435	0	0
Total	**195**	**351**	**4,946**	**9,677**	**17**	**35**

Table 14: Hudem PHC 2010-2011 Patient Details [32]

Over this time period the PHC saw 33.6% of its served population over all forms of care.

The snapshot of data available for the interruptions to Hudem PHC's power supply was shorter than others, but the data is presented in Table 15 with reliability data shown in Figure 27.

Interruption Pattern	Number of Interruptions	Duration (minutes)	Duration (hours)
Short Interruptions	**302**	**3,380**	**56.33**
< 15 Minutes	124	1,021	17.02
15 - 60 Minutes	79	2,359	39.32
Long Interruptions	**43**	**6,585**	**109.75**
1 - 3 Hours	32	3,257	54.28
> 3 Hours	11	3,328	55.47
Total	**246**	**9,965**	**166.08**

Table 15: Hudem PHC Grid Interruptions Details (March 25th - June 10th 2017) [37]

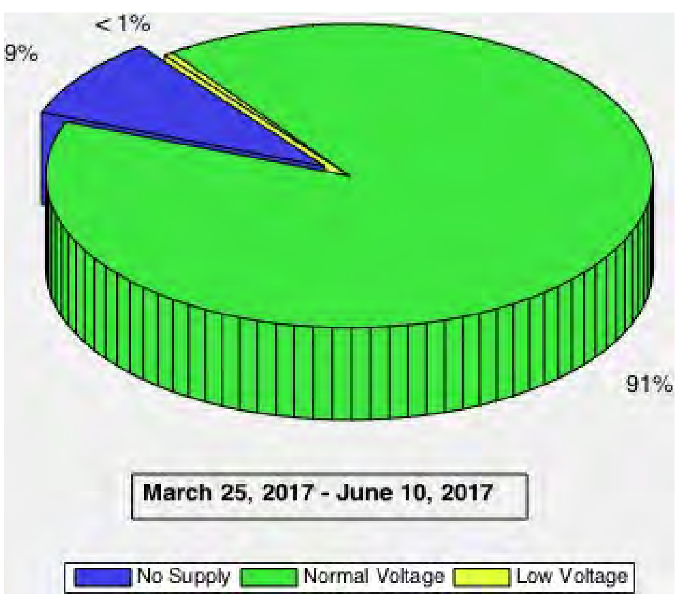

Figure 27: Hudem PHC Electricity Reliability Data[16][37]

As can be seen, Hudem PHC had normal voltage 91% of time over this roughly 2.5 month period. Similarly to Anegundi, this is a relatively high percentage in comparison to the other PHCs examined.

5.5.1 PV System Details

The system in Hudem is identical to that of Anegundi. It is a 2.65 kW system with 1,600 Ah of lead acid battery storage. The loads connected to this system are also the same as those of Anegundi and are summarized in Table 16

Section of PHC	Equipment	Quantity	Estimated Load [W]
Pharmacy	LED Tube Light	1	18
Senior Health Visitor	LED Tube Light	1	18
Refractionist Room	Deep Freezer	1	120
Toilet	LED Tube Light	2	18
Medicine Storage	LED Tube Light	1	18
Pathway	LED Tube Light	3	18
Dressing Room	LED Tube Light	1	18
Medical Officer Room	LED Tube Light	2	18
	Ceiling Fan	1	75
IPD	LED Tube Light	2	18
	Ceiling Fan	3	75
	Nebulizer	1	50
Labor Room	Baby Warmer	1	750
	LED Tube Light	2	18
	Ceiling Fan	3	75
	Suction Machine	1	250
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Computer	1	120
	Printer	1	360
Lab	LG Refrigerator	1	100
	Centrifuge	1	120
	LED Tube Light	1	18
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Water Purifier	1	50

Table 16: Hudem PHC Load Details

The effects of the implementation of the system are shown in Figure 28

[16] *Normal Voltage* is classified between 210V & 270V. *High Voltage* and *Low Voltage* is defined as being below 210V but greater than 0V.

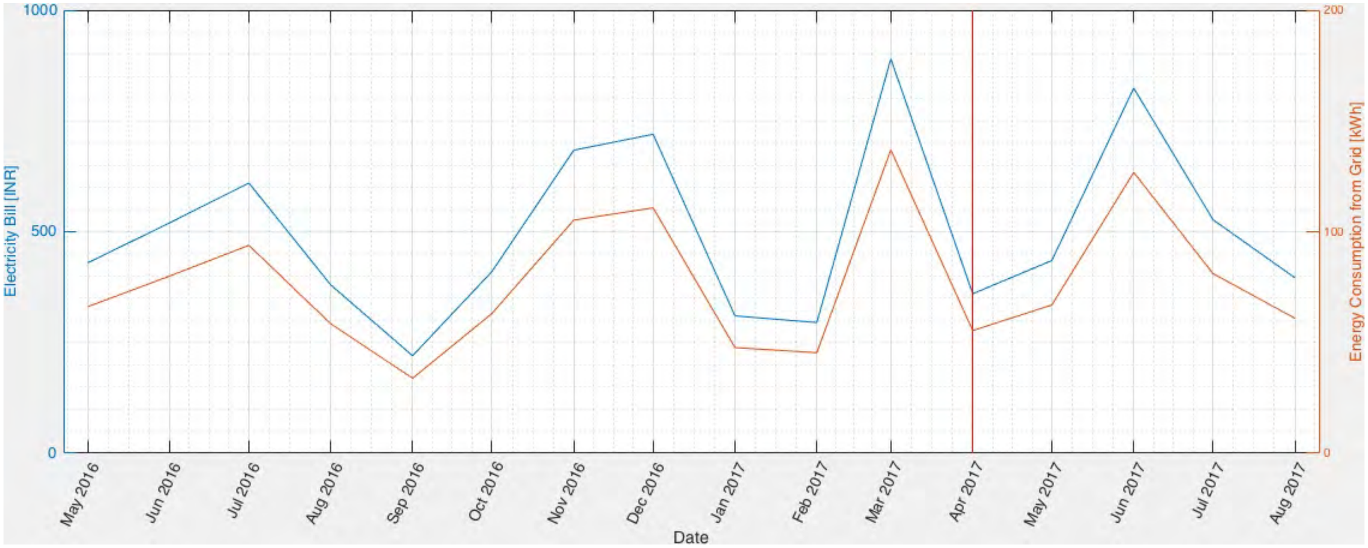

Figure 28: Hudem PHC Monthly Electricity Bills and Energy Usage

The results of the Hudem installation are shocking as it appears there is no real improvement in the electricity demand or the monthly electricity bill. In fact the average before the system was ₹486 while the average after was ₹546, an increase of ₹60. Upon further investigation, it was revealed that since the installation of the system there has been construction projects taking place at the Hudem PHC, which is leading to a higher electricity demand than normal. In order to truly see if there has been an decrease in the electricity demand from the grid, more data will be need to be gathered and analyzed over time.

5.6 SRR Pura PHC

Sriramarangapura, or SRR Pura, is located near Anegundi PHC however in the next district of Bellary. This PHC provides care for 24,122 people and oversees four SCs. The entrance to this PHC can be seen in Figure 29.

Figure 29: SRR Pura PHC

Interruption Pattern	Number of Interruptions	Duration (minutes)	Duration (hours)
Short Interruptions	**503**	**6,554**	**109.23**
< 15 Minutes	349	2,123	35.38
15 - 60 Minutes	154	4,431	73.85
Long Interruptions	**108**	**16,839**	**280.65**
1 - 3 Hours	88	9,119	151.98
> 3 Hours	20	7,7720	128.67
Total	**611**	**23,393**	**389.88**

Table 17: SRR Pura PHC Grid Interruptions Details (March 23rd - September 5th 2017) [38]

The interruptions of the SRR Pura PHC are similar to those of Anegundi and Hudem.

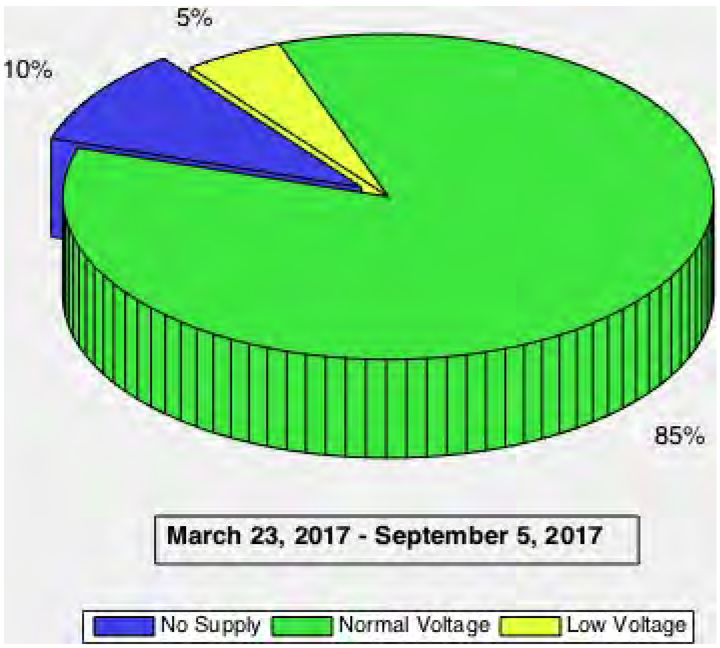

Figure 30: SRR Pura PHC Electricity Reliability Data[17][38]

SRR Pura had reliable power for 85% of the roughly five month sample period.

5.6.1 PV System Details

The system in SRR Pura is identical to that of Anegundi and Hudem. It is a 2.65 kW system with 1,600 Ah of lead acid battery storage. The loads connected to this system are also the same as the other two PHCs and are summarized in Table 18

Table 18: SRR Pura PHC Load Details

Section of PHC	Equipment	Quantity	Estimated Load [W]
Pharmacy	LED Tube Light	1	18
Senior Health Visitor	LED Tube Light	1	18
Refractionist Room	Deep Freezer	1	120
Toilet	LED Tube Light	2	18
Medicine Storage	LED Tube Light	1	18
			continued on next page

[17] *Normal Voltage* is classified between 210V & 270V. *High Voltage* and *Low Voltage* is defined as being below 210V but greater than 0V.

Table 18 – continued from previous page

Section of PHC	Equipment	Quantity	Estimated Load [W]
Pathway	LED Tube Light	3	18
Dressing Room	LED Tube Light	1	18
Medical Officer Room	LED Tube Light	2	18
	Ceiling Fan	1	75
IPD	LED Tube Light	2	18
	Ceiling Fan	3	75
	Nebulizer	1	50
Labor Room	Baby Warmer	1	750
	LED Tube Light	2	18
	Ceiling Fan	3	75
	Suction Machine	1	250
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Computer	1	120
	Printer	1	360
Lab	LG Refrigerator	1	100
	Centrifuge	1	120
	LED Tube Light	1	18
Office Room	LED Tube Light	1	18
	Ceiling Fan	1	75
	Water Purifier	1	50

The effects of the implementation of the system are shown in Figure 31

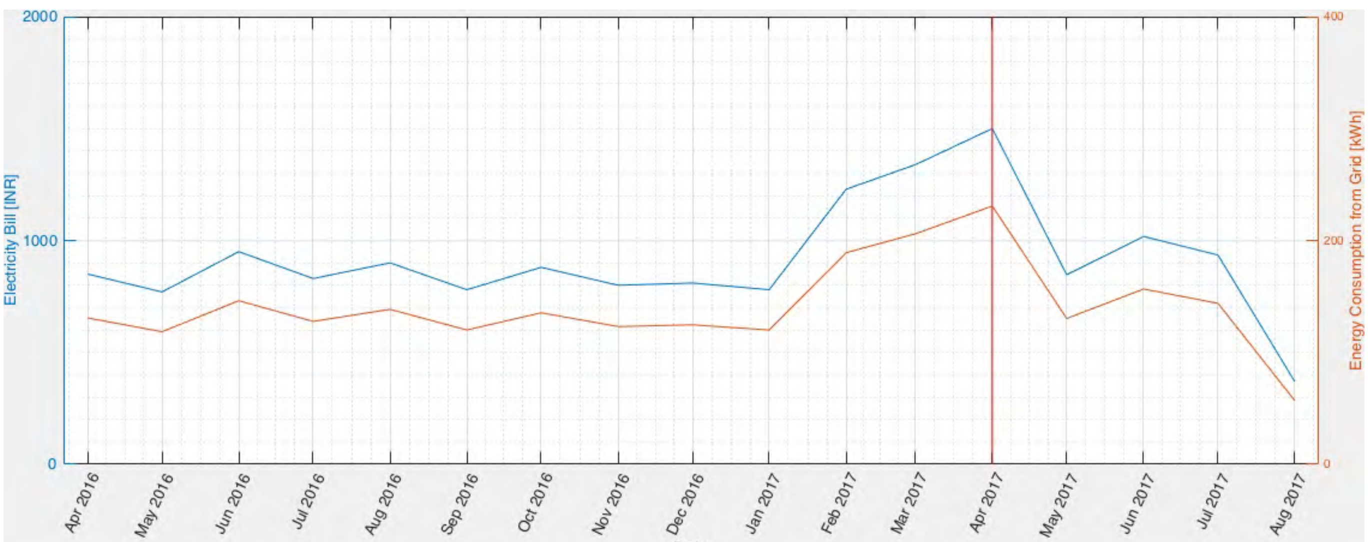

Figure 31: SRR Pura PHC Monthly Electricity Bills and Energy Usage

With the installation of the solar system, as marked by the vertical red line in Figure 31, there is a clear decrease in the demand from the grid and the monthly electricity bill. The average before the installation was ₹3,051 while the average after dropped ₹1,116 to ₹1,935 per month, almost half of the original. More time and data will be necessary to see if this savings is sustained.

5.7 Conclusion & Moving Forward

Throughout each of these PHCs there has been an average decrease in the amount of electricity needed from the grid as well as the associated monthly bill for this electricity[18]. On average there was a 31% savings in the monthly electricity bills of the PHCs[19]. More information will need to be gathered over time to ensure these savings are the new trends now that the systems have been put in place.

It will also be useful to watch the amount of patients each PHC is able to serve, to determine if there is any correlation between the installation of the new systems, the increased energy access, and the amount of service that can be provided. Data will need to be taken over the course of the year to be compared with that which has been collected in the past.

More data is needed to properly assess the function and performance of the solar PV systems. The SELCO Foundation is currently working to acquire to necessary data logging and energy metering equipment to monitor the power produced by the solar arrays in each PHC system, the discharge of the battery banks to feed the loads, the demand from the grid side, and as will be discussed in Section 6.6, the power production from the solar PV arrays for the vaccine refrigerators. With this information it will be possible to have a better understanding of if the systems are sufficiently meeting the needs of the PHCs, or if they are over/undersized. This information will then be able to help with future planning and implementation of solar PV systems in PHCs throughout India and can be replicated to other developing countries around the world.

These six projects in Karnataka are a good starting point, but many more will need to be carried out in order to reach all of the populations who rely on rural or trial PHCs with unreliable energy sources. Figure 32 shows the amount of PHCs active in India in government buildings in each state and union territory (UT). Since no state or UT has less than 76% of their PHCs in non-government buildings Figure 32 is indicative of the total amount of active PHCs in these locations. Karnataka is fortunate to have a relatively large amount of PHCs to provide health services to its population. Elsewhere in India this is not the case.

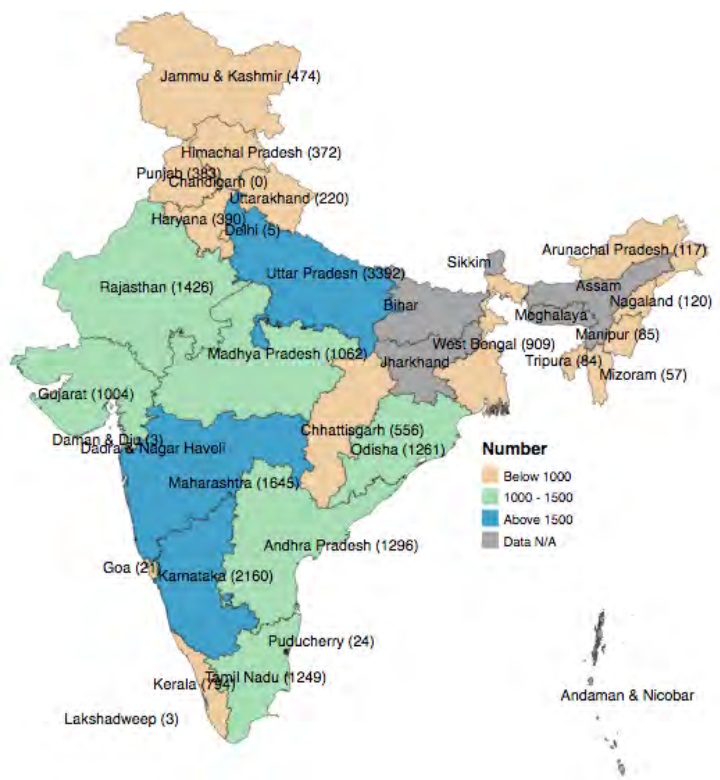

Figure 32: PHCs Functioning in Government Buildings of India as of 31st March 2014 [39]

[18] With the exception of Hudem PHC due to the construction work being carried out there

[19] 40% if not including Hudem PHC

If more PHCs are not put into commission, then the best alternative is to make sure the PHCs that are currently active have access to the energy they require to function and provide the services needed by their communities. As this section has shown, a viable option to provide this energy access is through the use of solar PV systems with battery storage. Another opportunity in these PHCs is to help power a set of critical devices for the long term health of the populations in these rural areas, vaccine refrigerators.

6 Solar Powered Vaccine Refrigeration

6.1 The Importance of Vaccinations

The advances in the medical field seen throughout the 20th century, and start of the 21st, have lead to an incredible increase in both the amount of lives saved, and the longevity of those lives. The widespread development and distribution of vaccinations in particular has directly lead to these progresses in the health of modern humans. It has been estimated that the use of vaccinations in the United States of America has prevented 103.1 million cases of contagious diseases since 1924 [40]. The United States' Centers for Disease Control and Prevention (CDC) reports that vaccination practices and programs such as the Vaccines for Children (VFC) program, have prevented more than 21 million hospitalizations and 732,000 deaths among children born in the last 20 years [41]. The WHO reports that vaccinated elderly individuals in the USA have a 50% lower risk of death than their unvaccinated peers [42].

Unfortunately these recorded benefits and progresses are not equally shared worldwide. Lack of basic healthcare and access to proper vaccines, are still major concerns in the developing nations of the world. Children in these areas are particularly vulnerable. As of 2014, it was estimated that 6.6 million children die every year from sickness, half of which are the result of preventable illnesses such as pneumonia and diarrhea [43]. Statistically, the main conditions these children face are pneumonia, diarrhea, malaria, measles, HIV/AIDS, as well as malnutrition [44]. The proportions of the diseases that caused child mortality in 2012 in the developing world is shown in Figure 33.

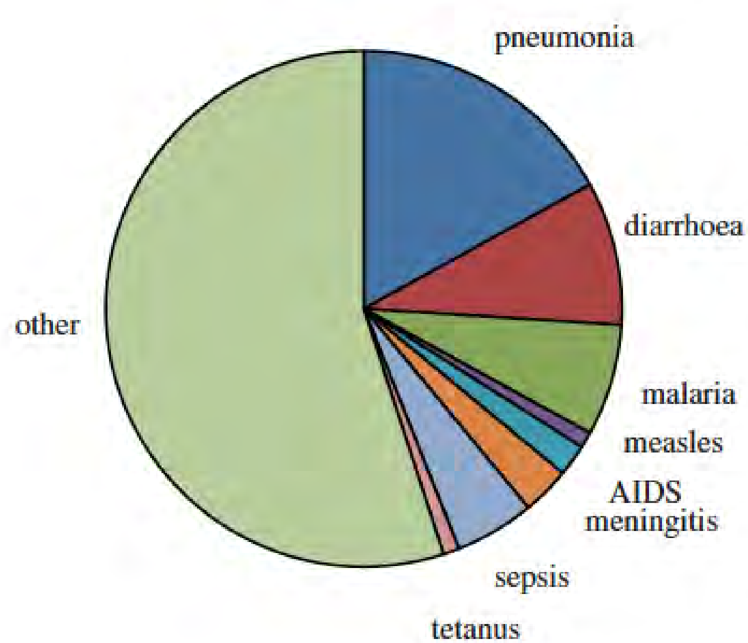

Figure 33: Infectious and Potentially Preventable Causes of Child Mortality in 2012 [43]

The need for increased inoculation in developing countries is evident, and there have been strides to make vaccinations more readily available to the vulnerable populations in these regions of the world. In 1974 the WHO established the Expanded Program on Vaccination (EPI) to increase the use and spread of vaccinations around the world. Since then, the spread of EPI vaccines has risen from covering 5% of the population in the targeted areas, to 80% [43]. However there are still significant portions of the global population lacking access to basic vaccines, and are therefore not immunized from these diseases.

6.2 Challenges of Vaccine Implementation in Developing Countries

Despite the successes of efforts such as the WHO's EPI program, the United Nations Children's Fund (UNICEF) estimates that over 30 million children around the world are lacking immunization [44], and as of March of 2017, the WHO estimated 19.4 million of them were infants without basic vaccinations [45]. UNICEF sites three main reasons for this current lack of immunization in developing nations [44]:

1. The vaccines are unavailable or out of supply in the area where they are needed [44].
2. The health services in the area are not well provided, or they are completely inaccessible to those who need them [44].
3. Families, and those who need the vaccinations, are uninformed or misinformed about when and why to bring their child, or themselves, in for immunization [44].

Each of these issues needs to be addressed appropriately to ensure the widespread distribution of vaccines to those who need them. In order to accomplish this, it is necessary to understand why these major obstacles are there to begin with. The root causes that contribute to this situation can be broken down into four different subcategories [46]:

1. **Structural and Demographic:**
   Assuming it is understood where the vaccines need to be delivered, inadequate infrastructure in developing countries can cause severe logistic issues when trying to get the proper vaccines to those who require them. This can be an issue anywhere in an unindustrialized nation, but it is further compounded when the vaccines need to be taken to more remote regions, which is often the case. Populations are currently growing in most non-industrialized nations, which results in a larger amount of vaccinations needed. There is also growing diversity in ways of life among these countries, which makes it more difficult to have a blanket solution to adequately cover an entire nation [46].

2. **Societal and Cultural:**
   The specific issues pertaining to society and culture will vary drastically between nation and region, however there are some large hurdles which are common across different groups. The level of poverty and lack of education of the citizens who need to be treated can be a very serious obstacle. This can cause a lack of financing for health care, as well as skepticism and doubt about the vaccines themselves. Religious taboos or superstitions may also impede the acceptance of vaccinations in a community. On top of this there may be a much stronger trust in more traditional medical practices. There also tends to be a lack of focus on preventative medicines, and rather a curative approach, which leaves less emphasis on the idea of immunization. This can be a difficult mindset to overcome when trying to highlight the benefits of becoming vaccinated [46].

3. **Economic and Political:**
   Developing nations tend to have limited resources and if the costs of vaccinations are high, then governments of these nations might focus on different priorities, or turn to alternative projects to spend their money on. There is also the issue of national pride and patriotism which is often overlooked. Citizens of developing nations may fear becoming dependent on industrialized nations for general aid, or the supply of vaccines. They may also view widespread vaccination programs with suspicion and could be wary of being exploited [46]. Some developing nations are able to help overcome this stigma by producing the vaccinations domestically.

4. **Medical and Scientific:**
   On top of these issues, un-immunized populations in developing nations tend to also be exposed to other health issues such as malnutrition, parasitic infections, among other complications. This can cause "altered immune status" among the recipients of the vaccines and could pose "potential problems with the mucosal delivery of the vaccines" [46]. On top of these issues, developing nations tend to not have adequate resources or a the scientific base for proper data gathering or surveying to understand the health of their population or the accessibility of vaccines [46]. This can make it very difficult to appropriately plan and coordinate the distribution of vaccines because it might not be known where the different types of vaccines are needed.

In order to have an efficient and effective supply of vaccinations to those who need them, all of these issues must be addressed. However, this report will focus more on the logistics and necessary physical storage of the vaccines, and possible areas of innovation in this field, so that vaccines can be ready and available to those who need them.

6.3 Proper Vaccine Storage

The proper storage and refrigeration of vaccines is absolutely critical to make sure that the vaccines retain their required potency upon use. If a vaccine loses this effectiveness and reliability, then there can be an inadequate immune response in the patient, which would continue to leave them susceptible to the disease in question. If that were to happen, the patient would need to be revaccinated in order to build up the necessary immunity to the disease. This also causes major financial losses due to the wasted vaccine and the subsequent need for replacement [47]. The WHO, in partnership with UNICEF, has stated:

> Experience shows that the national cold store remains the most critical element of an immunization system because this is where vaccines are received, stored and distributed in bulk. When there is an equipment or management failure at the primary level, large quantities of vaccine can be destroyed in a matter of a few hours. The immunization services of an entire country may thus be placed at risk and the financial loss can run to millions of dollars. This is no theoretical risk - it has happened [48].

On top of the potentially deadly consequences to those in need, and the possible financial loses, there is also a serious danger that storage errors such as this can cause a loss of confidence in the vaccination process among an already skeptical patient base. Therefore it is imperative that vaccines are properly stored from the time of manufacture until administration [49].

6.3.1 The Cold Chain

In order to reduce the chances of vaccines deviating out of their allowable temperature range and storage conditions, a system called the *cold chain* is utilized. The cold chain is the vaccine supply chain which ensures the vaccines are in proper conditions every step of the way, from manufacturing to administration in the patient. There are three crucial requirements that must be adhered to in order to ensure a successful cold chain system [50]:

1. The vaccines must be stored within the specified temperature ranges at all links of the cold chain.
2. The packaging and transportation of each vaccine must adhere to all of their listed requirements.
3. The vaccines must be within their specified conditions at the time of use and immunization in the patient.

A visual representation of how the cold chain works can be seen in Figure 34.

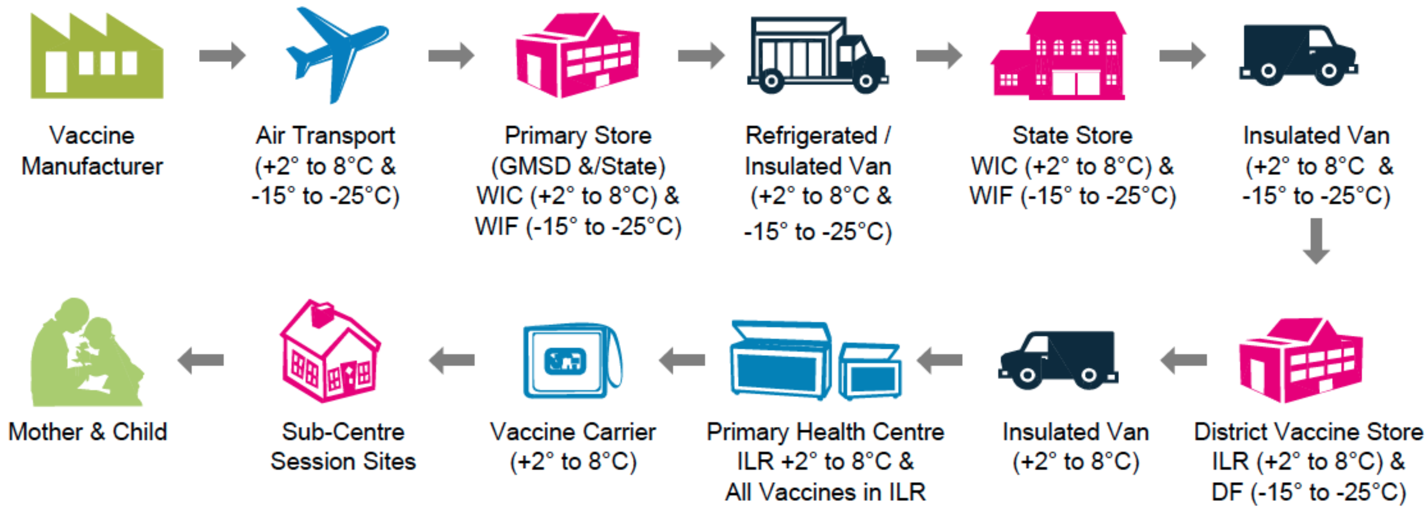

Figure 34: The Cold Chain [51]

The main factors that ensure a properly performing cold chain are the personnel involved in the process, the equipment that is used to achieve the necessary temperatures and transportation, and the procedures that are in place to make sure the vaccines maintain their potency [51]. In more remote locations, where primary health centers are isolated from other communities and lack reliable electricity, it can be a challenge to keep their vaccines within the required temperature range.

Different vaccines are susceptible to different parameters, whether it be heat, freezing, or light. Each vaccine is vulnerable to differing amounts of these variables. With this in consideration, vaccines are categorized into six distinct groups: A through F. Group A being most sensitive to heat and group F being least sensitive [50]. Figure 35 shows which vaccines are listed in each of these groups.

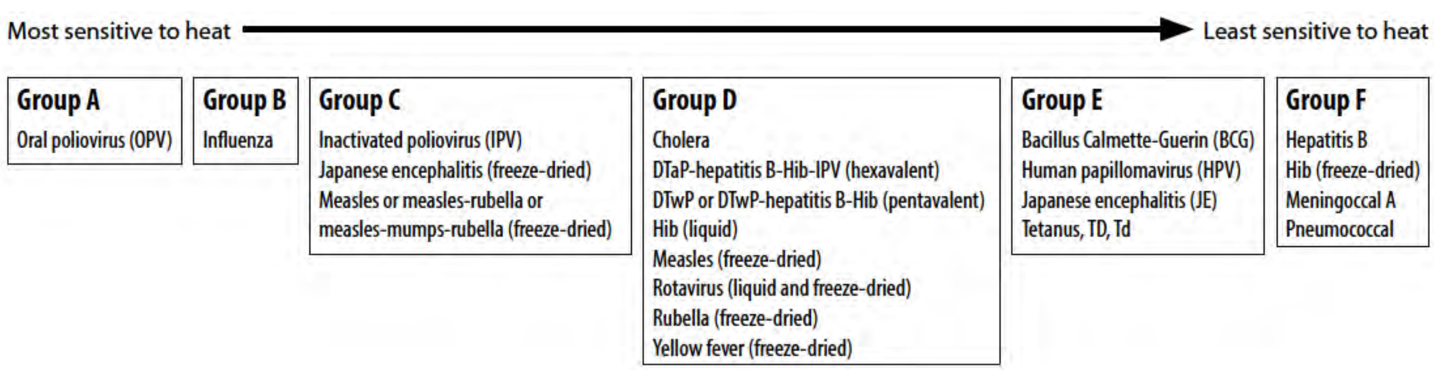

Figure 35: Vaccine Heat Sensitivity Groups [50]

Some of the specific vaccines that are sensitive to light or freezing can be seen in Table 19:

Vaccine Type	Freeze Sensitive	Light Sensitive
Cholera	✓	
DTaP-hepatitis B-Hib-IPV (hexavalent)	✓	
DTwP or DTwP-hepatitis B-HiB (pentavalent)	✓	
Hepatitis B (Hep B)	✓	
Hib (liquid)	✓	
Human papillomavirus (HPV)	✓	
Inactivated poliovirus (IPV)	✓	
Pneumococcal	✓	
Rotavirus (liquid and freeze-dried)	✓	
Tetanus, DT, Td	✓	
BCG		✓
Measles		✓
Measles-rubella		✓
Measles-mumps-rubella		✓
Rubella		✓

Table 19: Freeze and Light Sensitive Vaccines [50]

Vaccines that are sensitive to light should be kept in dark glass vials as a protection measure, but a secondary packaging is still always necessary to ensure they are properly shielded from sunlight or strong artificial light. Those that are sensitive to freeze must be kept within their temperature requirements throughout the entire cold chain [50].

Many of the vaccinations listed above are among those that are most commonly required in remote areas of developing countries. Therefore it is incredibly important to take their specified tolerances and conditions into account throughout their lifespan and throughout the cold chain, in order to make sure they reach the patient to successfully immunize them.

Most vaccines need to be kept between 2°C and 8°C in order to maintain their required potency. In order to achieve these temperatures and adequate storage conditions throughout the cold chain the proper technologies must be used. Refrigerators, cold boxes, and vaccine carriers are all used regularly [50].

6.3.2 Technologies Not to be Used

It is important to note that vaccine refrigeration systems are not to be confused with refrigerators that the general public is more familiar with. Common household combined refrigerators & freezers **are not recommended** for use in vaccine storage because they have been found to be less capable of maintaining the required storage temperatures for vaccines. Most systems are set up so the air from the freezer will blow directly into the refrigerator compartment, which could directly influence the temperature of any vaccines stored inside. If a household unit must be used, then it is recommend that only the refrigerator compartment be used, and the freezer be turned off [52].

Dorm & bar style refrigeration units **should never be used** because their freezer temperatures can not be maintained within the required tolerances for many vaccines. On top of this, there is often not proper separation between the freezer area and the refrigeration unit, which causes the cold air from the freezer to severely influence the refrigeration temperature and cause instability and inconsistency [52]. Example photos of these types of refrigeration systems can be seen in Figures 36 and 37 [52].

Figure 36: Household Fridge & Freezer (**Not Recommended)**

Figure 37: Dorm & Bar Style Fridge (**Do Not Use)**

6.3.3 Vaccine Refrigeration Technologies

Different types of refrigerators can be used in order to achieve the specified temperature ranges and conditions for proper vaccine storage. The most common methods fall in three different categories [50]:

1. *Compression Units*: conventional grid connected refrigeration units
2. *Photovoltaic Units*: solar powered refrigeration systems
3. *Absorption Units*: refrigeration systems which are powered by bottled gas or kerosene

Electric compression refrigerators are currently the most common form of vaccine storage. They tend to be preferable in locations where there is a reliable electricity source. However, in situations where this is not the case, where electricity is either very unreliable or not available at all, photovoltaic or or absorption refrigerators could be much more appealing (depending on the solar resource and conditions of the area) [50].

In order to determine which of the three categories of vaccine refrigeration are most suitable, it is necessary to take an in-depth look into what each of the technologies can offer.

6.3.3.1 Grid Powered Electric Refrigerators (Compression Units)

On-grid compression units currently make up the majority of vaccine storage devices. These refrigerators have been tried and tested in the field and benefit lot of governmental support across the globe. This technology is seen as the ideal choice in areas with a reliable electricity supply. The most common style are ice lined refrigerator (ILR) technologies, which are units that form a layer of ice around their storage chamber. These devices have specific handling and operating instructions as the temperatures within the refrigeration chamber fluctuates as the distance from the ice-lined walls varies. Therefore certain vaccines must be kept in specific conditions to ensure they are kept at the proper temperatures and do not get too cold or freeze. Different types of the compression units can be seen in Figure 38

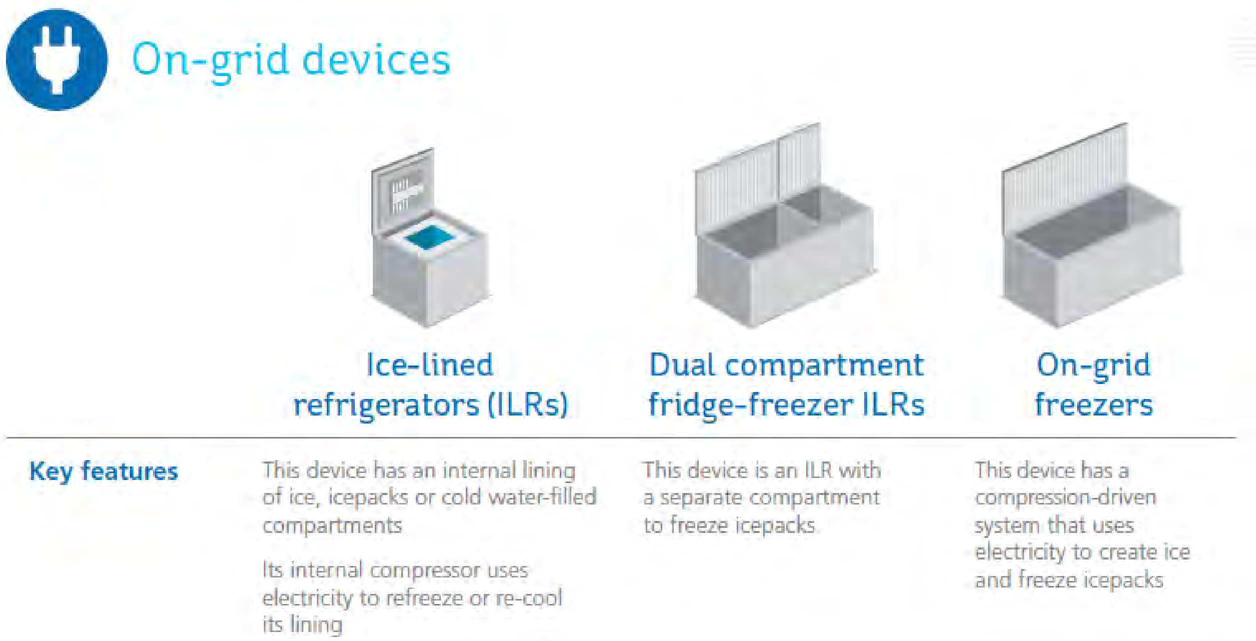

Figure 38: Compression Unit Types [53]

As of the writing of this document, compression units still remain cheaper than photovoltaic units on average, and they have years of field data to draw from when determining if they are the proper fit for an application. Their largest drawback is that they very difficult to use in situations without an adequate supply of electricity, such as remote or underserved areas. There are also some complaints from those who use them when it comes to the specifications of where the vaccines can be stored within the refrigerator itself to avoid freezing.

6.3.3.2 Solar Powered Refrigerators (Photovoltaic Units)

In situations where electricity is either very unreliable or not available at all, solar powered refrigerators can be much more appealing (depending on the solar resource and conditions of the area) [50]. Solar powered refrigerators (photovoltaic units) can be broken down into two separate categories: solar battery-powered refrigerators and solar direct drive (SDD) refrigerators. Example diagrams of these types can be seen in Figure 39.

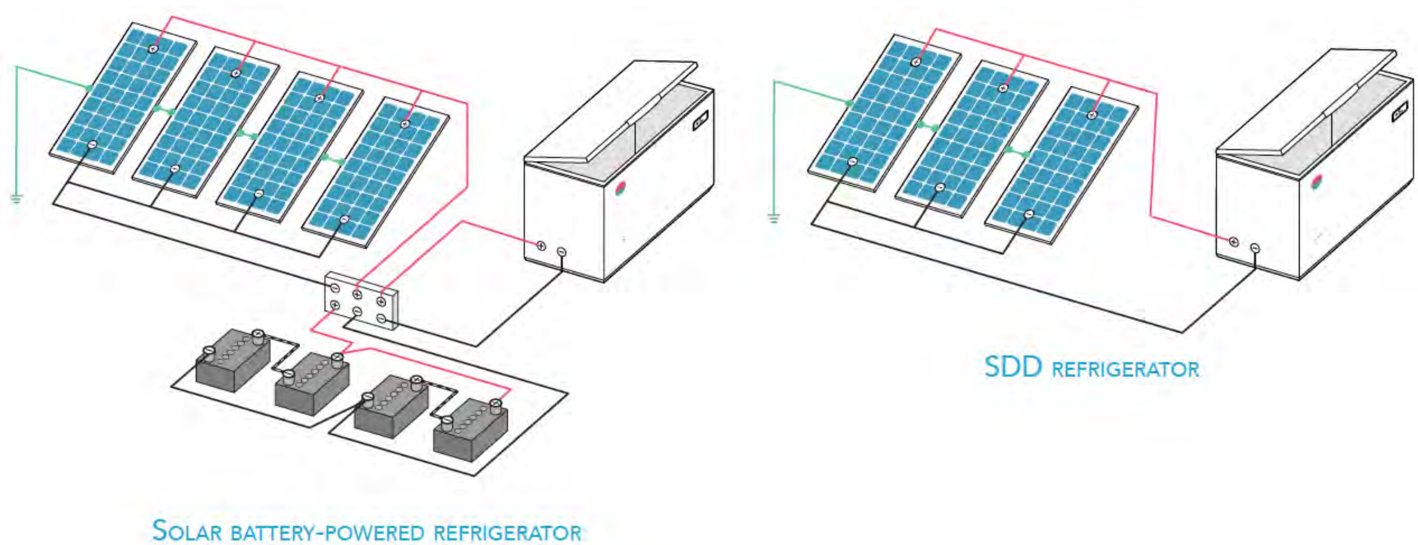

Figure 39: Photovoltaic Unit Types [54]

Solar battery-powered units can use the electricity that is produced from the photoelectric effect of the PV panels to power a refrigeration compression cycle to keep the stored vaccines within the required temperature range. They also have the ability (as their name suggests) to store this charge in a battery bank to be used later for powering the refrigeration when the solar resource is insufficient or unavailable (e.g. because of inclement weather or during the night) [54].

SDD refrigerators on the other hand, only have the ability to directly power the compression cycle with the electricity produced from the solar PV array. When solar energy is available a level of thermal storage is produced. Different systems have varying means of achieving this, but the general principle is to produce as much ice as possible (or cooling another cold storage material or refrigerant) and then use that in different ways to regulate the refrigeration compartment and the temperature of the vaccines it is holding [54].

SDDs have an economic advantage, in the fact that the battery technology is usually the most vulnerable and expensive component that will need the most regular replacement of a photovoltaic unit. By circumventing the need for a battery bank, SDDs tend to have "the lowest total cost of ownership in areas with unreliable electricity and suitable solar irradiance" [54].

6.3.3.3 Gas Powered Refrigerators (Absorption Units)

Absorption units use a combustable gas as a fuel source (most often kerosene or propane), to create a gas of their coolant (usually ammonia). This heat can then be used to run a refrigeration cycle and drive the cooling process of the storage chamber of a refrigerator [55]. As will be detailed Section 6.3.4, absorption technology is no longer a very viable option, so the details of this technology will not be explained further.

6.3.4 Comparison of Refrigeration Technologies

Before solar photovoltaic (PV) technologies reached their sophistication and low costs of recent years, absorption refrigerators were considered to be the best solution in situations where electric grid connections were unreliable. However, there were various problems with these systems which lead to keeping vaccines within the 2^{o}C to 8^{o}C range both difficult and expensive [54].

This is due to the fact that it is often difficult to get a consistent supply of the necessary fuel for absorption refrigerators in the areas where they are required. It is also common that the gas or kerosene could be used for other purposes and the proper storage of the vaccinations could be neglected. Absorption refrigeration is also less efficient than the compression process used in compression and photovoltaic units. Absorption units require frequent maintenance, and they use fossil fuels to run, which increase local air pollution and global greenhouse gas emissions [54].

With these factors in consideration, it is the recommendation of the author that when the solar resource permits, it is preferable to apply a photovoltaic unit instead of an absorption unit for vaccine storage.

When comparing compression units with photovoltaic units, other factors must be considered to choose the correct option.

6.4 When to Use Solar Vaccine Refrigerators

Solar vaccine refrigerators can be appealing alternatives to compression units depending on the situation where the refrigerator is being installed. The WHO recommends photovoltaic units for regions that have less than 4 hours of reliable electricity per day, while Gavi: The Vaccine Alliance recommends using them for regions with less than 8 hours of electricity per day or power outages that last longer than 48 hours [56]. However, studies and simulation modeling have been conducted by collaborating researchers from:

- HERMES Logistics Modeling Team, Baltimore, MD and Pittsburgh, PA, USA

- Pittsburgh Supercomputing Center, Carnegie Mellon University, Pittsburgh, PA, USA
- Public Health Computational and Operations Research (PHICOR) and Global Obesity Prevention Center (GOPC), Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA

In summary their:

> Results suggest that WHO and Gavi guidelines may be appropriate but conservative, as the actual thresholds at which solar refrigerators can provide value may include places with more reliable electricity [...] Though current solar devices were more costly than electric refrigerators when no power outages occurred, introducing even small numbers of daylong electrical outages demonstrated the improvements in performance and efficiency that SDDs can offer over ILRs in areas with substantially more reliable electricity than those indicated by current guidelines [...] While the WHO and Gavi guidelines may be helpful in identifying places that require off-grid solutions in order to function the majority of the time, these guidelines may not capture all situations where solar devices could offer benefits that outweigh their costs [56].

This study and its simulations were conducted based on the cold chain and immunization practices in Mozambique in early 2017. This helps to highlight how photovoltaic units can still be the best option even if electricity is relatively reliable in a given area. Graphical representations of when solar vaccine refrigeration units can become more cost competitive than on-grid systems can be seen in Figures 40 and 41. These are broken down into district level systems and systems for health facilities (which service a larger patient base).

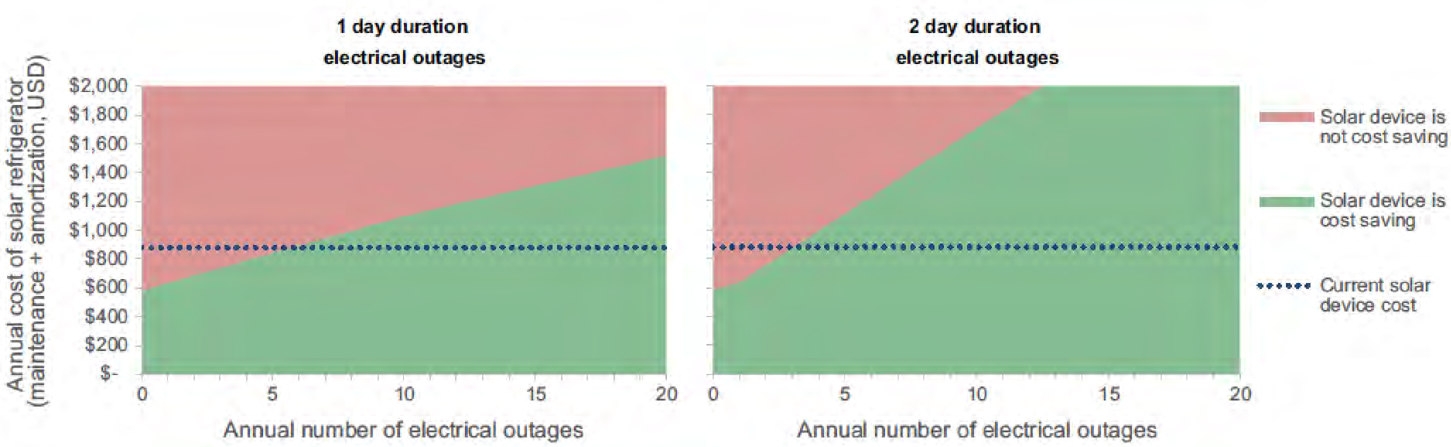

Figure 40: Photovoltaic Unit Savings vs. Compression Units (District Level)[20][56]

[20]"The maximum annual cost for each district-level solar device (including amortization and maintenance) that can provide savings over electric mains-powered refrigerators in total cost per dose administered is shown when electrical outages of varying frequency and duration occur at all district level locations. Results assume the electric refrigerator holdover time exceeds the duration of the outage" [56].

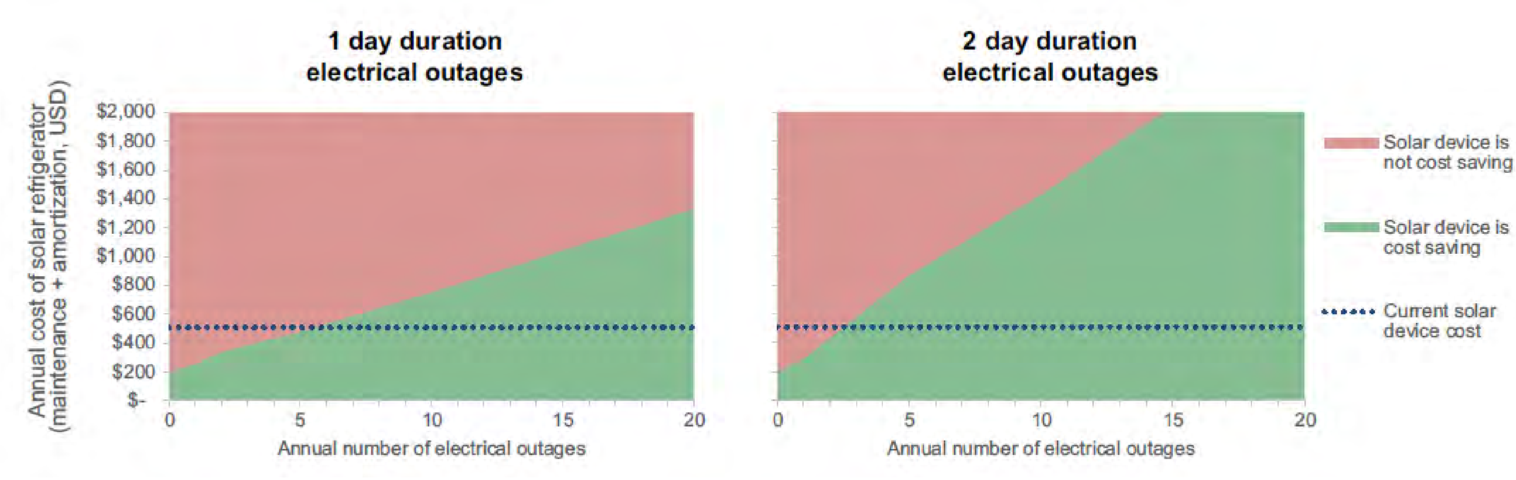

Figure 41: Photovoltaic Unit Savings vs. Compression Units (Health Facilities)[21] [56]

For the purposed of the SELCO Foundation, the results in Figure 40 may be more relevant as it deals with units applied in smaller scale district centers. As can be seen, if there are situations where power outages that last for one day occur approximately six times per year, then photovoltaic devices can be the most practical and cost effective choice. If these power outages last for two days and they occur roughly three times in a year, then it is possible that solar devices could also be the better choice.

6.5 Solar Powering Vaccine Refrigeration

As mentioned in Section 6.3.3.2, there are two main types of vaccine refrigerators which can power their refrigeration cycle through the use of solar photovoltaic panels, solar battery-powered systems, and solar direct drive systems (SDD). Among these types, there are numerous makers and models to consider.

When analyzing these different models for use in the field, it's important to have a clear comparison to determine which would be most effective with the parameters of a given application. A solid place to begin the search is with systems that have been prequalified by the WHO to be used in the field for vaccine storage. As of October 4, 2017 the WHO had approved the amounts and types of photovoltaic units as shown in Table 20.

Photovoltaic Unit Category	**Number of Units with Prequalified Vaccine Freeze Protection**	**Total Number of Prequalified Units**
SDD	21	34[22]
Solar Battery Powered Systems	0	3
Total	**21**	**37**

Table 20: WHO Prequalified Photovoltaic Units [57]

As can be seen, SDD systems make up the majority of pre-approved systems due to their benefits to battery systems as detailed in Section 6.3.3.2.

[21]"The maximum annual cost for each solar device (including amortization and maintenance) that can provide savings over electric mains-powered refrigerators in total cost per dose administered at the health facility level is shown when electrical outages of varying frequency and duration occur at all health facilities. Results assume the electric refrigerator holdover time exceeds the duration of the outage" [56].

[22]3 of these SDD devices required small ancillary batteries to power a cooling fan. This battery requires periodic replacement throughout the life of the device

6.5.1 Godrej SureChill Solar Direct Drive Refrigerators

Considering the large amount of SDD refrigerators that are WHO prequalified, the SELCO Foundation decided to work with one in particular, the SureChill SDD. SureChill has partnered with Godrej for distribution of the systems in India. The system has been specifically designed with vaccine storage in mind. The technology behind it relies on the fundamental physical properties of water (H_2O). H_2O has a very unique property of being most dense at roughly 4^{o}C [58].

With this in mind, the SureChill refrigerator compartment is surrounded with a chamber that is filled with water. During the day, while the sun is shining and power can be produced with its partnering PV panels, a refrigerating compression cycle is run to produce an ice storage above the refrigerator compartment. A heat exchanging system is used to cool the water in the chamber with this ice storage. As the water cools to 4^{o}C it will be most dense, and will fall through the channels in the surrounding chamber, to the area of the refrigeration compartment, keeping the compartment, and everything in it, at 4^{o}C. When the water warms, it will rise, come back into contact with the ice block and the cycle will continue as long as there is a reservoir of ice in the upper compartment. The 4^{o}C temperature lies ideally within the 2^{o}C-8^{o}C vaccine storage requirements [59]. A visual representation of this process can be seen in Figure 42.

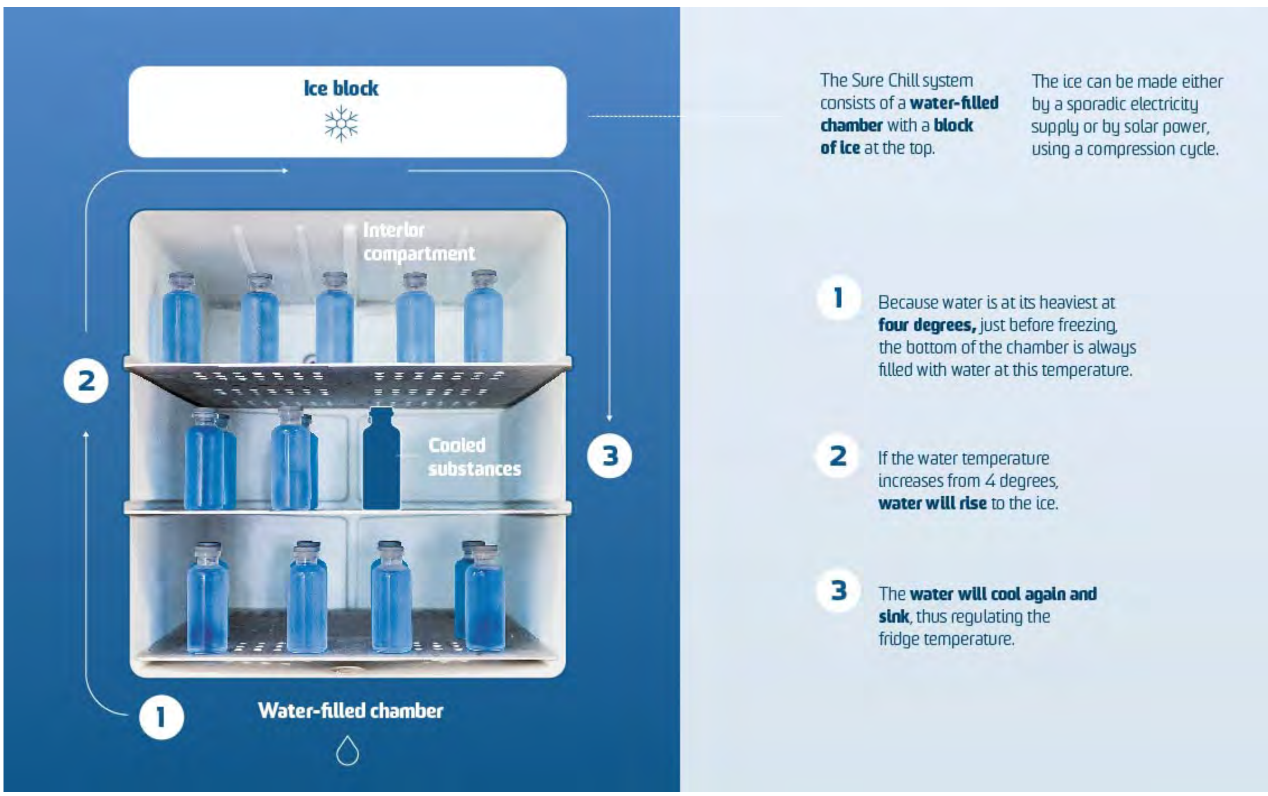

Figure 42: SureChill Diagram [60]

With this technology, SureChill states that vaccines can be kept for 10 days or more without power [59].

Unfortunately, these systems are on average twice as heavy as normal refrigeration systems which adds some complexity to transportation and moving around the site they are installed [60].

6.6 Data and Field Studies

The SELCO Foundation has installed SureChill systems in various PHCs throughout the country that would benefit from having a stand alone vaccine refrigeration system such as this. Some of these PHC that now have these devices are extremely isolated and are only accessible via poorly maintained mud roads which can prove to be very difficult to navigate. They are prone to power outages, some of which can last weeks at a time. This puts them well within the recommendations of the WHO for implementation of a SDD system. Some are also in an areas where temperature can reach upwards of 45°C, so proper refrigeration of vaccines is crucial.

A breakdown of the PHCs where the SureChill devices have been installed is shown in Table 21.

State	PHC Name
Karnataka	Anegundi
	GH Koppa
	Hudem
	Kannura
	SRR Pura
	Gumballi
Arunachal Pradesh	PHC Anpum in Lower Dibang Valley District
	Sangram
	Tarasso
Meghalaya	PHC Umkiang in East Jaintia Hills
	PHC Saipung in East Jaintia Hills
Assam	Jorhat Boat Clinic
Orissa	Swasthya Swaraj Kannigumma Health Center
	Swasthya Swaraj Kerpai Health Center
Chhattisgarh	MCHC-MSF Bijapur

Table 21: PHCs in India with SureChill Units

Because of these PHC's characteristics and conditions, they were good fits for a solution such as the SureChill to meet it's cold storage needs and provide vaccines of the required potency to the surrounding community. The SureChill that has been installed is a model GVR50DC solar direct drive vaccine refrigerator. Its technical specifications can be seen in Table 22

Dimensions	122 x 79.5 x 75 cm (HxLxD)
Gross Storage Capacity	57.7 L
Vaccine Storage Capacity	46.5 L
Energy Source	Solar Direct Drive
Solar Array Details	Multicrystalline Panels 470 W_p
Power Consumption @ 43°C	$0.85 \ \frac{kWh}{24hours}$
Refrigerant	R600a
PQS Code	E003/049
Weight	125 kg[23] & 95 kg[24]
Quality Standard	ISO 9001:2008
Holdover Time	5+ days

Table 22: SureChill GVR50DC Specifications [61]

Having a refrigeration system such as this can dramatically help overcome the hurdles seen at these PHCs. The unit that was installed in Anegundi PHC can be seen in Figure 43.

[23] weight of refrigerator

[24] weight of solar system

Figure 43: SureChill in Anegundi PHC

The storage chamber of the Anegundi PHC's SureChill unit is shown in Figure 44.

Figure 44: SureChill Storage Chamber in Anegundi PHC

The size of this storage chamber is the same across of all of the units that the SELCO Foundation has helped implement in the PHCs discussed.

The 470 W multicrystalline solar array that powers the refrigeration cycle of the SureChill unit is shown in Figure 45.

Figure 45: SureChill PV Array in Anegundi PHC

This photo is of the array installed on the roof of the Anegundi PHC.

6.6.1 Initial SureChill Testing

Before these systems were implemented, preliminary testing of a SureChill system was carried out at the SECLO Foundation headquarters in Bangalore, India. Beginning in the evening of March 10th 2016 a SureChill refrigerator was turned on from an ambient temperature of 20.6°C. The recorded temperature data can be seen in Figure 46.

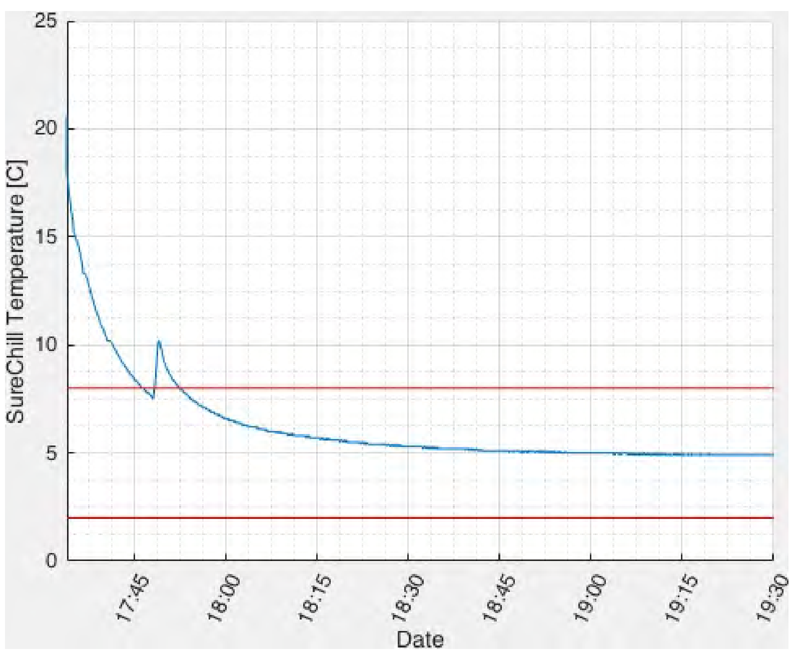

Figure 46: SureChill Starting Temperature Data

As can be seen, the refrigerator was initially able to drop down below the 8°C maximum within roughly 15 minutes. However after that there was another spike in temperature, perhaps due to some sensing equipment registering the end of the duty cycle of the refrigerator. In total it took the refrigerator roughly 45 minutes to reach a stable temperature of about 5°C.

The associated power production of the solar array for the SureChill refrigerator during this period can be seen in Figure 47 (this power is equivalent to the power consumed by the refrigerator to build up its thermal storage).

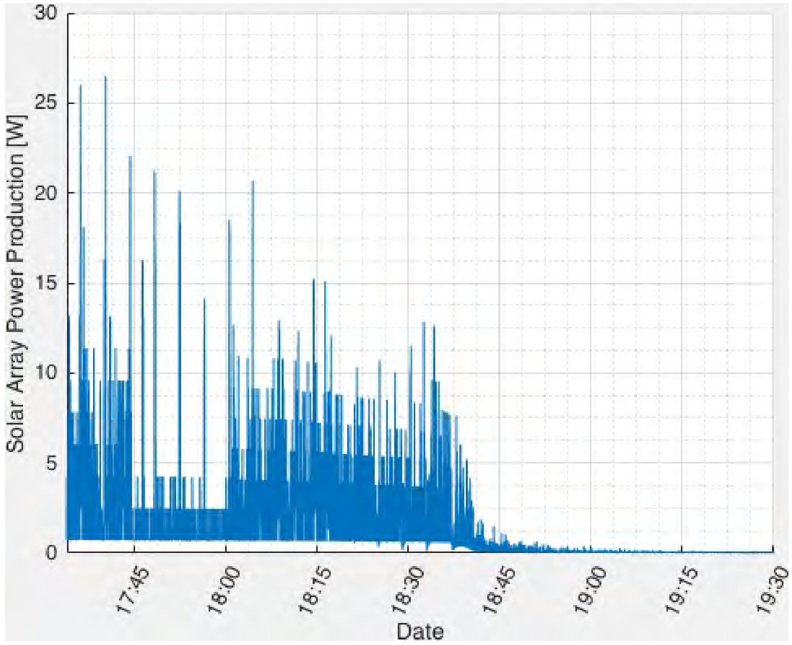

Figure 47: SureChill Starting Power Data

Sunset for that day was at 18:30. As can be seen the power produced by the PV array tapers down to zero as that time approaches.

Besides initial cool-down data, constant running tests were also conducted with the same unit at the Bangalore headquarters. Beginning at midnight on March 12th 2016, the SureChill refrigerator was tested for 46 hours. The resulting running temperature data can be seen in Figure 48.

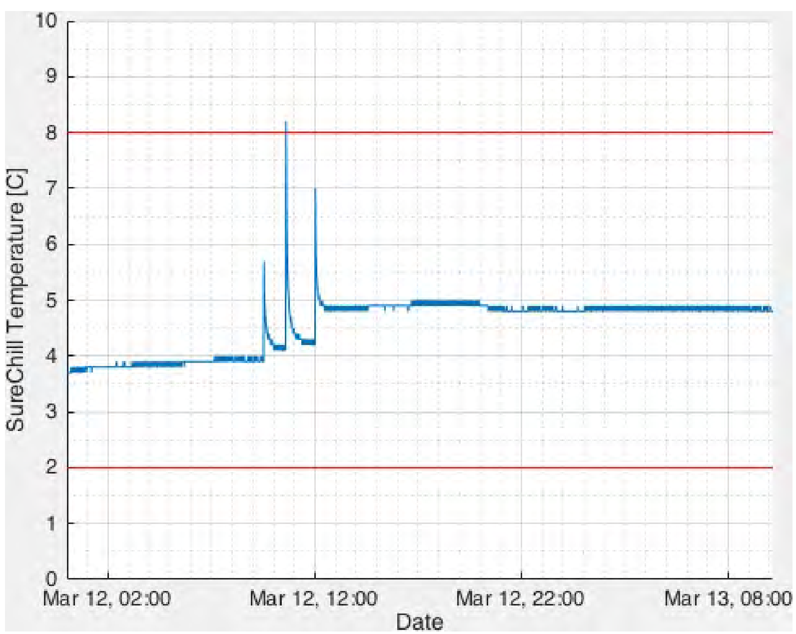

Figure 48: SureChill Running Temperature Data

The temperature of the refrigeration chamber was within the required temperature limits for the majority of the testing time, however there were three spikes in temperature. These spikes are associated with the opening and closing of the refrigerator doors which took place during the test. Once the doors were closed and remained so, the temperature began to stabilize at roughly 5ºC.

The associate power consumption of the SureChill refrigerator during this period can be seen in Figure 49.

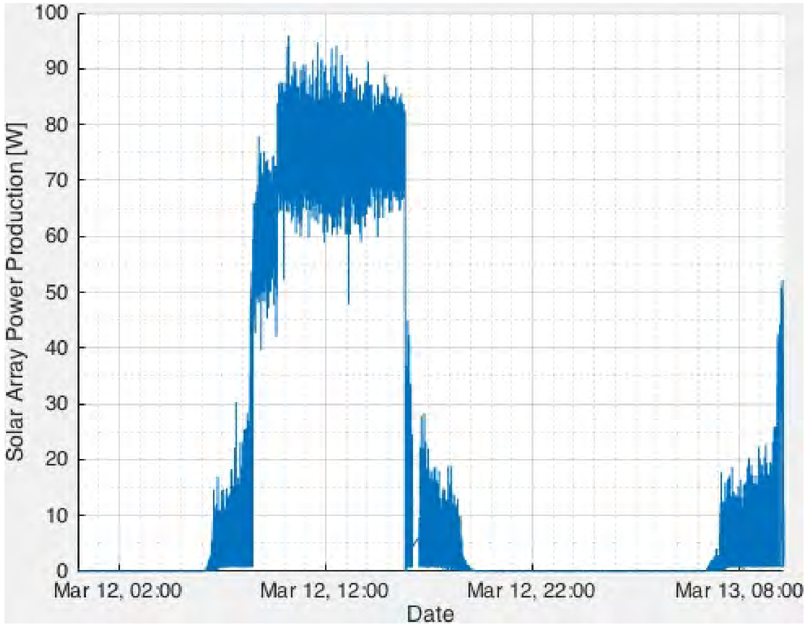

Figure 49: SureChill Running Power Data

When comparing Figure 49 to Figure 47 it is clear how much more power production there is from the PV array during the midday hours. A spike in power production can be seen at roughly the first temperature spike as well, indicative of the system attempting to reel its temperature back within the required limits.

6.6.2 PHC SureChill Field Data

Of the PHC locations that were listed in Table 21, the rest of this report will focus on those which have been installed in the six Karnataka locations. These are the same PHCs which have been detailed in Section 5. There locations be can be seen on the map of Karnataka and southern India in Figure 15 of that same section.

Data was collected in two separate ways, automatically with a data logging system where temperature of the chamber was recorded every 10 minutes, and another method by the pharmacist of the PHC reading the temperature and hand writing it twice a day (normally at 9:00 and 17:00).

The data logging method was only successfully employed for two PHCs during this trial period. The temperature data over a course of roughly 5 months for the Anegundi PHC is shown in Figure 50

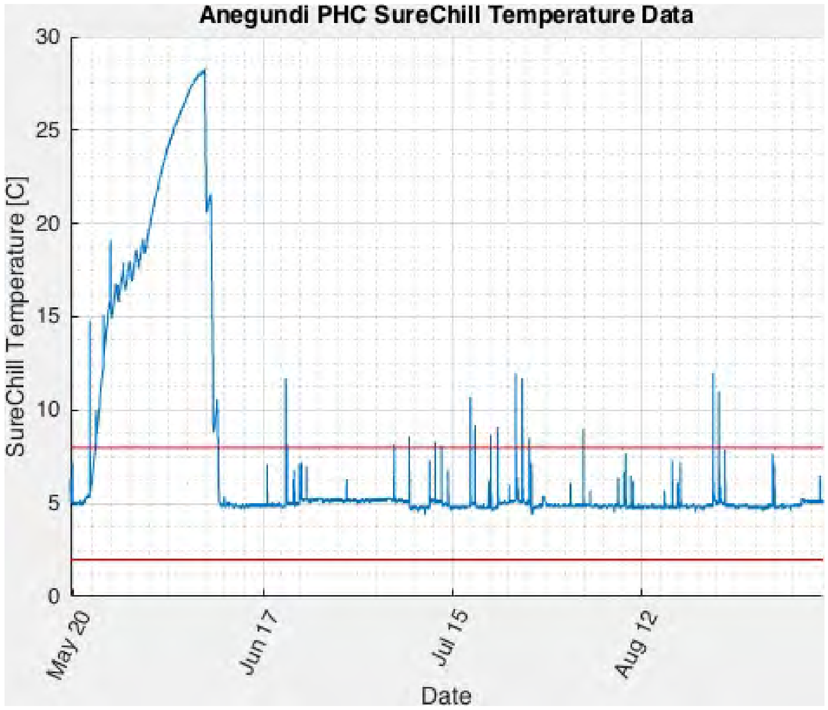

Figure 50: Anegundi PHC SureChill Temperature Data

As can be seen there was a very large spike in temperature between the end of May and mid June. This was due to a broken ventilation fan of the of the SureChill system that has since been resolved. However, throughout the course of the following months there were several instances of the temperature rising above the 8°C limit for short periods of time.

Data was also collected for the Anegundi SureChill unit by hand and is shown in Figure 51

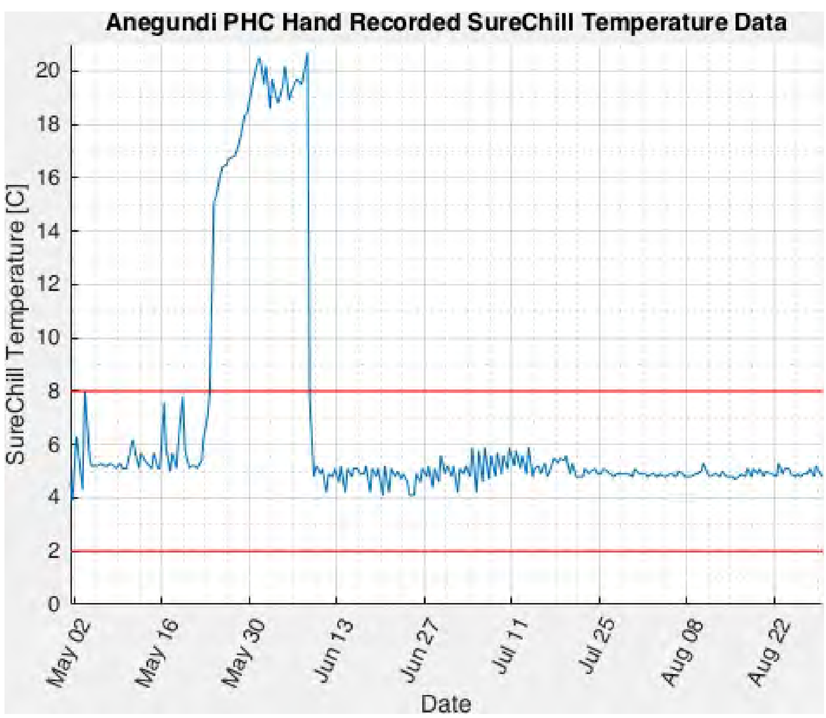

Figure 51: Anegundi PHC Hand Recorded SureChill Temperature Data

As can be seen, the time period where the SureChill had a defective component is clearly visible, however the consequent temperature spikes seen in Figure 50 are not shown in 51. There are various factors that could potentially explain this, but a few possible explanations could be:

- The temperature spikes were caused by the opening and closing of the refrigerator, which would not have been monitored with only two recordings a day, after the temperatures would have stabilized again.
- There is a defective issue with the SureChill, however it was only evident in between the times of hand monitoring the temperature.
- There were errors or negligent behavior when recording the refrigerator temperatures by hand.
- There was a technical issue with the data logging units which falsely recorded these temperature spikes.

Hand collected data was collected for the the subsequent PHCs shown in Figures 52 to 55

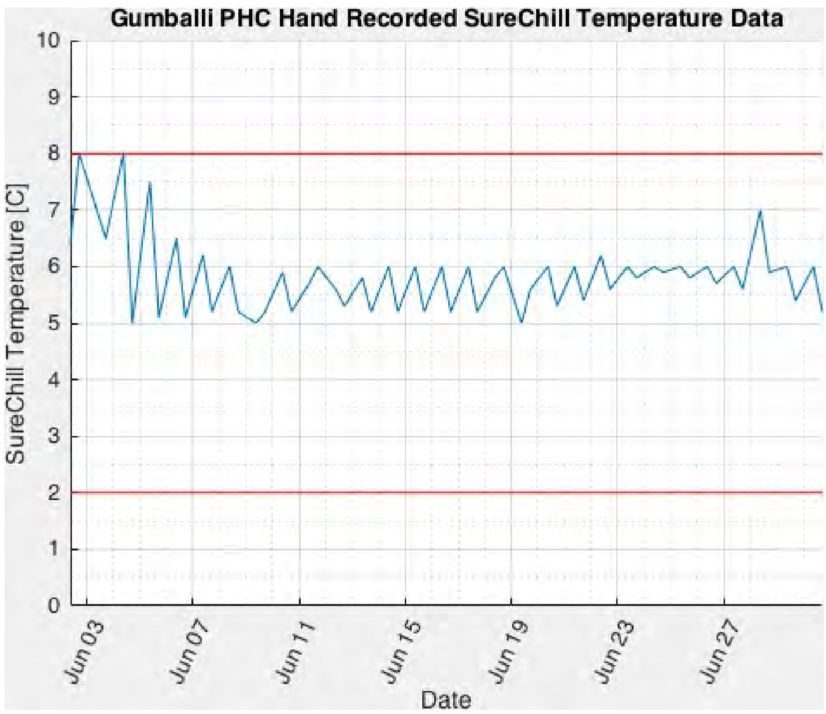

Figure 52: Gumballi PHC Hand Recorded SureChill Temperature Data

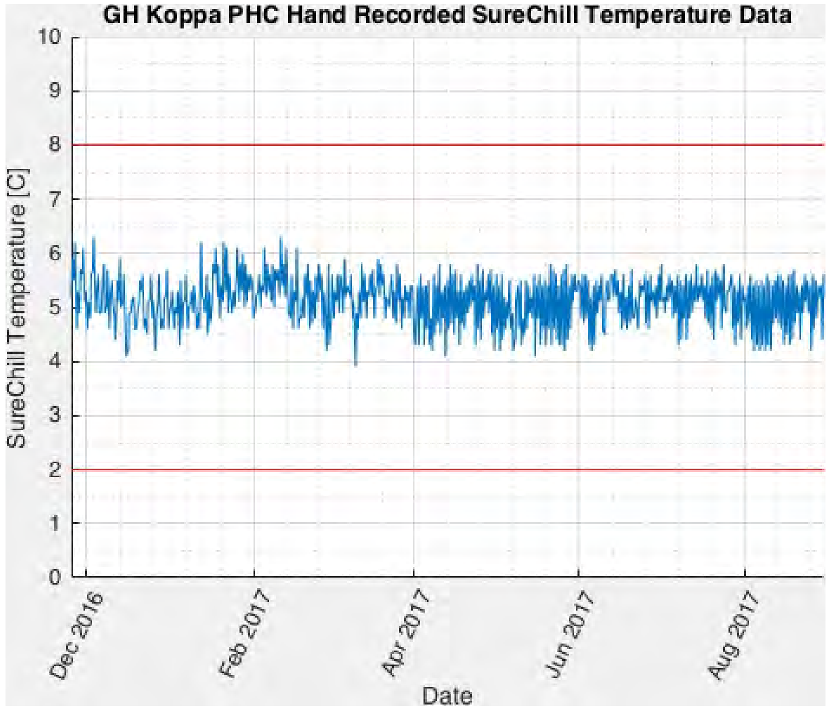

Figure 53: GH Koppa PHC Hand Recorded SureChill Temperature Data

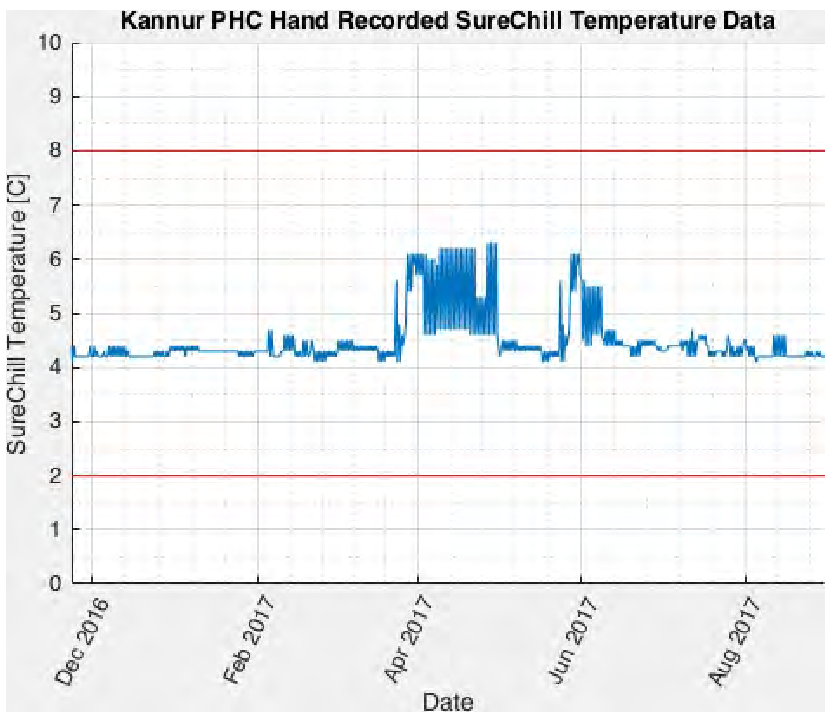

Figure 54: Kannur PHC Hand Recorded SureChill Temperature Data

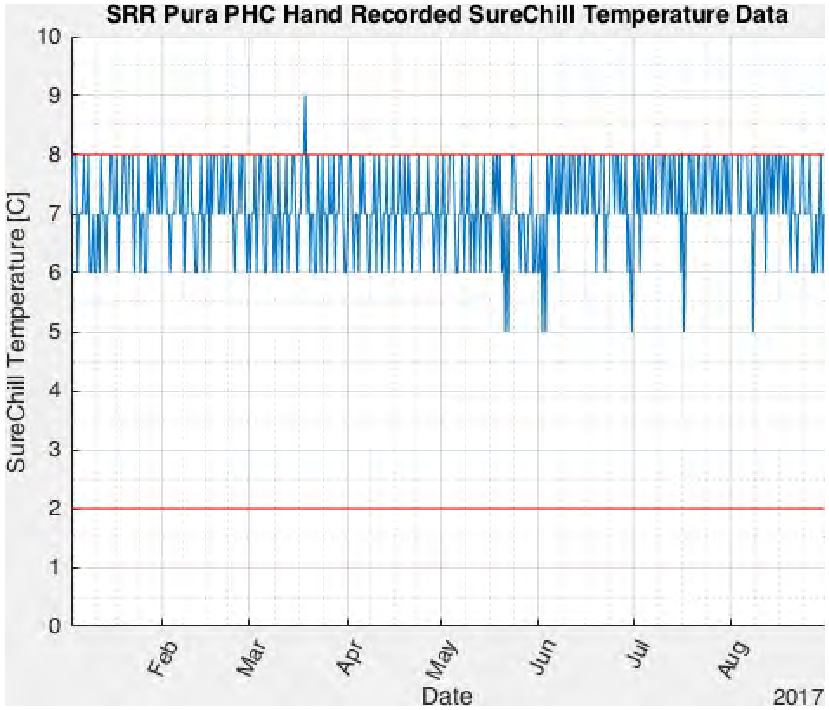

Figure 55: SRR Pura PHC Hand Recorded SureChill Temperature Data

With the exception of a small deviation recorded at the SRR Pura PHC as shown in Figure 55 (and the Anegundi data as previously discussed) all of the hand recorded data falls within the 2ºC - 8ºC limits.

6.6.3 SureChill PHC Surveying

Along with the technical evaluation of the SureChill devices, surveys were taken of all of the PHCs, and discussions had with the pharmacists of the focus PHCs. The general consensus of those using the systems was that they approved of them and found them easy to utilize. Consistently there were references to the fact that the design of this system doesn't allow any vaccines to freeze, as is possible in classic ILR systems. My pharmacists claimed this was a huge benefit and helped mitigate the chances of accidentally loading the vaccines incorrectly and losing them.

However, some pharmacists in the PHCs felt the storage chamber was too small, although non of those surveyed were using them to their full capacity. Another common theme among the PHCs is that they were not using them to house many vaccines. In most cases they would only host excess vaccines that the PHC didn't have room for in conventional cold storage devices, and sometimes the SureChill devices would be completely empty. When questioned about this, many of the PHC staff members claimed they did not know if they have formal government approval to implement these devices, so rather than risk being penalized, they opted not to use them.

6.7 Conclusion & Recommendations

It is clear after analyzing the different possibilities of vaccine storage that the best system will have to be chosen on a case by case basis. However, based on the work and research that has been conducted on this subject, it can be stated that if any situation meets the basic requirements of at least Gavi's requirements as mentioned in Section 6.4 (i.e. less than eight hours of electricity per day or power outages lasting longer than 48 hours), then photovoltaic devices such as the SureChill should be implemented.

It is important to also analyze any situation where there are at least six power outages a year that last for more than one day, as also mentioned in Section 6.4. In these situations it can be possible that a device such as the SureChill will save money and also allow for a greater number of vaccines to be distributed to the local community it is serving.

When implementing a photovoltaic unit such as the SureChill SDD unit, it is highly recommended to have a data logging system to keep a constant watch on the temperature of the vaccines in the refrigeration chamber. This can be done in tandem with the conventional method of twice daily hand recorded measurements, but the consistent data throughout the day can be crucial to making sure a system is behaving properly, and vaccines are not at risk of being lost to temperature deviations.

As of the time of this writing, SELCO Foundation is in the process of procuring more of the data logging systems that were used for the Anegundi and Kannur PHCs and will implement them throughout all of the other SureChill units that they have deployed. This study will continue to evaluate the performance of the SDD refrigerators and their impact on PHCs abilities to storage and deliver these crucial vaccines to the patient bases that they serve.

On top of this, it is crucial to have government officials formally approve the use of the SureChill and any other SDD devices that have been WHO prequalified for use in these PHCs. Without this it seems many of the devices will not be used to their full potential. Having these devices sit around unused is a disservice to the communities that could potentially benefit from their implementation.

7 Solar Powered Boat Ambulance in Odisha, India

As discussed in Section 2.1, geographic accessibility is a major target area in order to ensure rural inhabitants have access to the proper health services that they need. Grappling with this issue is at the heart of serving rural and tribal regions of developing countries. By definition they are extremely remote, and this isolation of their communities puts a disconnect between the location of the required health services and the end users.

Assuming the relocation of the communities themselves is not an option, the best ways to deal with this geographic separation is by either bringing the hub of the services closer to the community (i.e. building more PHCs closer to these communities), or by facilitating an easier means of transporting the services and the patients to and from each other (i.e. creating some sort of shuttling service).

This case study focuses on the later option, using solar PV technology to provide a sustainable means of providing health services to a series of geographically isolated tribal communities in the Indravati Power Station Reservoir in India.

7.1 The Indravati Power Station Reservoir

The Indravati Power Station Reservoir is located at 19.292^{o}N, 82.817^{o}E (19^o 17′ 31.2", 82^o 49′ 1.1994"), in the state of Odisha (formerly Orissa) in eastern India. Its location within the country can be seen in Figure 56. It is nested between the borders of three separate districts: Kalahandi, Nabarangapur, and Koraput.

Figure 56: Location of Indravati Reservoir in India [62]

As of 2011, these three districts had population densities of: 199 $\frac{\text{People}}{\text{km}^2}$, 230 $\frac{\text{People}}{\text{km}^2}$, and 156 $\frac{\text{People}}{\text{km}^2}$ respectively. These three southwestern localities are among some of the most scarcely populated of Odisha, as can be seen in Figure 57. The districts are bordered in red, with the location of the Indravati Reservoir at the junction of all three.

Figure 57: Population Density of Odisha's Districts [63]

The region surrounding the Indravati Power Station Reservoir is very sparsely populated, and difficult to reach from outside of the area. This isolation and remoteness directly impacts those who inhabit this portion of the state.

7.2 Health of Tribal Communities in the Region

7.2.1 Current Situation

The area around the reservoir is home to various tribal communities. Due to the seclusion of the region surrounding the reservoir, these people are left with very limited medical facilities and most often rely on traditional healers and methods for any health issues that may arise. Community assessments have shown that there is widespread anemia among women, as well as high instances of malnutrition among the children in these communities. It's been reported that malaria, diarrhea, scabies, pneumonia, and tuberculosis are the most prominent diseases and conditions found among the people in the area. These conditions could be easily treated, were it not for the isolation and separation of the communities there.

There are also severe issues primarily with the process of pregnancy and delivery within the communities in this region. Assessments of the population have shown that women commonly perform traditional practices during the labor process, which involves isolating themselves during labor and to deliver the baby themselves. In an attempt to ease the difficulties of this process, women are encouraged to eat less during the pregnancy in an attempt to limit the growth and size of the baby, which leads to underweight and malnourished infants. After delivery, the baby is most often bathed in the open waters of the reservoir which commonly results in pneumonia of the newborn.

In the event that the peoples of this region were to seek outside help with medical issues or emergencies, they would have to take a long and perilous journey by land in order to reach the nearest health center.

7.2.2 Kerosene Powered Boat Ambulance

In an attempt to alleviate these severe health issues within the reservoir population, a kerosene powered boat ambulance was introduced to travel between the villages in the region on March 30th, 2016. This boat can be seen in Figure 58. The project was jointly introduced by:

- *The Orissa Voluntary Health Association (OVHA)* - a civil society organization that promotes health for the people of Odisha [64].
- *Basic Aid (BASAID)* - is "a charitable organization that supports small projects around the world through direct developmental aid" [65]
- *Tata Trusts* - a non-sectarian philanthropic organization which provides assistance in natural resource management, rural livelihoods, education, healthcare, among many other sectors around India [66].

Figure 58: Kerosene Powered Boat Ambulance

The ambulance has been used to transport medical staff and health workers in an effort to spread health education, modern medical practices, as well as medication and other services. It can also be used to transport patients from their communities to the docking station of Kamalaguda[25] where they can be taken by land to the nearest PHC in Adri, located 4 kilometer (km) away.

The reservoir spans a length of roughly 40 km, however only a portion of it, and the communities in that area, are serviced by the current kerosene powered boat ambulance. This area is highlighted in Figure 59.

[25] marked by a star in Figure 60

Figure 59: Serviced Area of Indravati Reservoir [67]

Since the introduction of this boat ambulance, there has been a significant reduction in these dangerous health practices of the tribal communities. However, they are still being carried out in many villages located farther away from the villages along the banks of the reservoir. The villages that the boat ambulance currently services are shown in Figure 60.

Figure 60: Serviced Village Locations [68]

Unfortunately kerosene is often unavailable in the reservoir region, so running the boat can often become a challenge. On average, the ambulance runs out of kerosene once a month and is not able to be used for at least a week. When the boat is able to function, it averages 3 or 4 station visits along the reservoir in a day, and goes out on voyages roughly 5 days a week. Most often the boat will return to Kamalaguda to dock overnight.

The distances from different villages around the reservoir can be seen in Table 23.

Origin	Destination	Distance [km]
Kamalguda	Adri[26]	4
Kamalguda	Mahulpatna	2
Mahulpatna	Kumudasil[27]	0.5
Kumudasil	Lepespadar[28]	0.5
Lepespadar	Kenduguda[29]	0.5
Kenduguda	Upparchabri	1
Upparchabri	Sanchhatrang	0.5
Sanchhatrang	Fukijal	0.5
Fukijal	Padepadar	2
Padepadar	Benakhamar	1
Benakhamar	Talangai GP Villages[30]	2 to 5

Table 23: Distances Between Docking Locations

The boat travels an average distance of 2 to 5 km without a halt, and a maximum non-stop distance of roughly 10 km. When at a village, the ambulance may be docked there up to 3 hours depending on the situation. The boat travels roughly 20 $\frac{\text{km}}{\text{day}}$ when in operation.

The current ambulance has a length of 8.2 Meter (m), a breadth of 2.2 m, a depth of 0.85 m, and can fit 12 passengers. The ambulance utilizes a Yamaha EK25B kerosene outboard motor for its propulsion. It has an average travel speed of 20 $\frac{\text{km}}{\text{hr}}$ during its operation and uses roughly 10 $\frac{\text{L}}{\text{hr}}$, or 200 $\frac{\text{L}}{\text{hr}}$. Considering the irregularity of the supply of kerosene in the region, there has been a desire to shift to an alternative fuel source which is more abundant and readily available in order to provide this same service for the health of the tribal communities.

7.3 Solar Powered Boat Ambulance

In an effort to combat the unreliability of the kerosene supply while still providing health care to the local population, a solar powered boat ambulance is being investigated as a replacement. This presents a large challenge and requires a feasibility analysis to determine if it is a viable option. This process begins with a proper assessment of the solar resource in the reservoir area.

7.3.1 Solar Resource

As explained in Section 4.2.1 analyzing the solar resource in a given area is mandatory to determine if the project is viable or not. The region of the Indravati Power Station Reservoir has an average annual direct normal solar irradiance (DNI) between 4.5-5.5 $\frac{\text{kWh}}{\text{m}^2\text{day}}$ [69], as can be seen in Figure 61. The region of interest has been highlighted by a red box. The region also has an average annual GHIs between 5.0-5.5 $\frac{\text{kWh}}{\text{m}^2\text{day}}$ [69], as can be seen in Figure 62. The region of the reservoir has been highlighted by a blue box.

[26] Adri is the location of the closest PHC, it is accessible from Kamalguda by land
[27] Kumudasil is located north of the region shown on the map
[28] Lepespadar is located north of the region shown on the map
[29] Kenduguda is spread between a location on the eastern shore and an island in the middle of the reservoir
[30] Talangai GP Villages are located south of the region shown on the map. There are several different villages, hence the range in distances

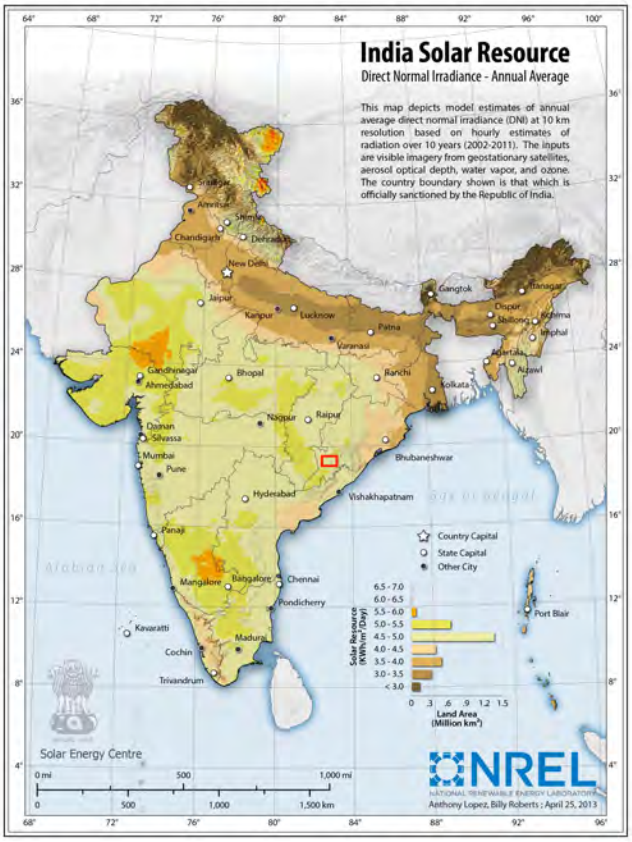

Figure 61: Direct Normal Irradiation (DNI) [69]

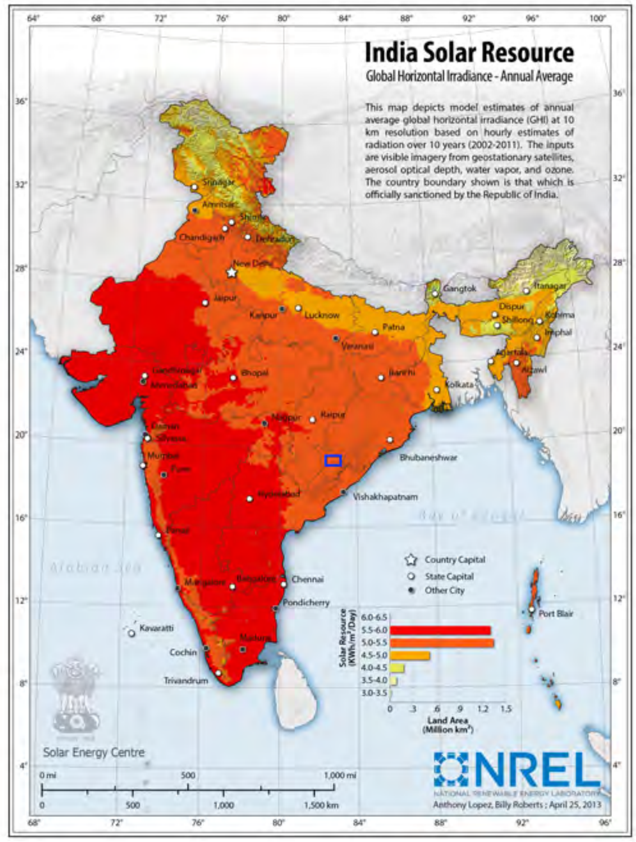

Figure 62: Global Horizontal Irradiation (GHI) [69]

Using the exact coordinates of the reservoir, it is possible to get more refined GHI data to determine the viability of a solar system in the area. Solar irradiation and meteorologic data collected from the National Aeronautic and Space Administration (NASA) and NREL can be seen in Tables 24 and 25.

Month	**Clearness Index**	**Daily Radiation (GHI) ($\frac{kWh}{m^2 day}$)** [31]
January	0.643	4.88
February	0.655	5.61
March	0.631	6.12
April	0.615	6.48
May	0.569	6.19
June	0.405	4.43
July	0.328	3.57
August	0.331	3.51
September	0.427	4.24
October	0.543	4.81
November	0.610	4.75
December	0.637	4.63

Table 24: Monthly Average Solar Global Horizontal Irradiance (GHI) and Clearness Index Data [70]

[31] The solar irradiation data provided is an average taken over a 22 year period from July 1983 to June 2005.

Month	Air Temperature (^oC)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Wind Speed ($\frac{m}{s}$) [32]	Earth Temperature (^oC)	Heating Degree-Days (^oC-d)	Cooling Degree-Days (^oC-d)
January	20.1	52.9	95.9	2.6	21.9	7	308
February	23.2	49.1	95.7	2.7	26.0	0	366
March	27.1	43.0	95.5	2.9	31.1	0	525
April	28.5	51.5	95.3	3.1	32.2	0	551
May	29.9	53.7	94.9	2.9	33.6	0	617
June	27.5	72.7	94.7	2.9	29.2	0	521
July	25.6	81.0	94.8	2.9	26.5	0	479
August	25.0	82.9	94.9	2.9	25.6	0	460
September	24.9	79.9	95.1	2.1	25.7	0	448
October	23.7	72.1	95.5	2.4	24.5	0	426
November	21.6	56.6	95.8	2.8	22.6	0	349
December	19.5	51.4	96.0	2.7	20.7	4	294
Annual	24.7	62.2	95.3	2.8	26.6	11	5344

Table 25: Surface Meteorological Data [70]

With this data, it was possible to generate estimates of the average solar irradiation for any particular time of day, throughout the whole year. This was done by first assuming the irradiation would follow a sinusoidal function. Knowing the average values of the GHI as given in Table 24, the peak of the sine wave could be calculated for each month given equation 3 [71].

$$I_{peak} = \frac{\pi I_{avg}}{2} \tag{3}$$

Where:

- I_{peak} is the peak irradiation value of the function (given in Table 24) [$\frac{\text{kWh}}{\text{m}^2\text{day}}$]
- I_{avg} is the average irradiation of the function [$\frac{\text{kWh}}{\text{m}^2\text{day}}$]

Therefore, the average peak irradiation value for a given day in each month could be calculated for the reservoir region. With this value determined, it could be used to generate a sinusoidal function of the irradiation with respect to the time of day, given equation 4 [72].

$$I(t) = I_{peak} sin(2\pi f t + \phi) \tag{4}$$

Where:

- t is the time of day [s]
- $I(t)$ is the irradiation as a function of t [$\frac{\text{kWh}}{\text{m}^2\text{day}}$]
- I_p is the peak irradiation value of the function [$\frac{\text{kWh}}{\text{m}^2\text{day}}$]
- f is the frequency (the number of oscillations that occur per second) [Hz]
- ϕ is the phase, or offset of the equation [radians]

[32] The wind speeds were measured at a height of 10 m

In order to determine the frequency parameter for this function it is necessary to know the period, which in this case is the length of 1 day (24 hr or 84,600 s), therefore the frequency can be calculated as shown in equation

$$f = \frac{1}{T} \tag{5}$$

Where:

- f is the frequency (the number of oscillations that occur per second) [Hz]
- T is the time required to complete one cycle [s]

The phase offset (ϕ) in this situation would be the time of sunrise converted to radians via the relationship of $\frac{2\pi[\text{radians}]}{T[\text{s}]}$. This value will change every day, so an average value was chosen to represent each month. The times of sunset, sunrise, and the duration of daylight were taken for the 15$^{\text{th}}$ day of each month throughout 2017. These values can be seen in Table 26.

Month	Sunrise [hrs][33]	Sunset [hrs][34]	Length of Day [hrs]
January	6.60	17.68	11.08
February	6.47	17.98	11.52
March	6.13	18.15	12.02
April	5.70	18.28	12.58
May	5.42	18.45	13.03
June	5.35	18.65	13.30
July	5.50	18.68	13.18
August	5.67	18.47	12.80
September	5.78	18.05	12.27
October	5.90	17.62	11.72
November	6.12	17.35	11.23
December	6.42	17.40	10.98

Table 26: Sunrise, Sunset, and Day Length Data for the 15$^{\text{th}}$ of Every Month in 2017 [**?**]

Finally, taking into consideration the average length of daylight for each month, the GHI data can be converted from an incident energy value [$\frac{\text{kWh}}{\text{m}^2\text{day}}$] to an incident power value [$\frac{\text{kW}}{\text{m}^2\text{day}}$] via equation 6.

$$I_{month} = \frac{GHI_{month}}{Daylight_{month}} \tag{6}$$

Where:

- I_{month} is the average solar irradiance for a given month [$\frac{\text{kW}}{\text{m}^2\text{day}}$]
- GHI_{month} is the average Global Horizontal Irradiation for a given month [$\frac{\text{kWh}}{\text{m}^2\text{day}}$]
- $Daylight_{month}$ is the average length of a day in that month [hr]

With all of the necessary values calculated and obtained, the average daily solar irradiance in each month could be calculated and plotted as a function of the time of day, as can be seen in Figure 63

[33]Values calculated on a 24hr clock
[34]Values calculated on a 24hr clock

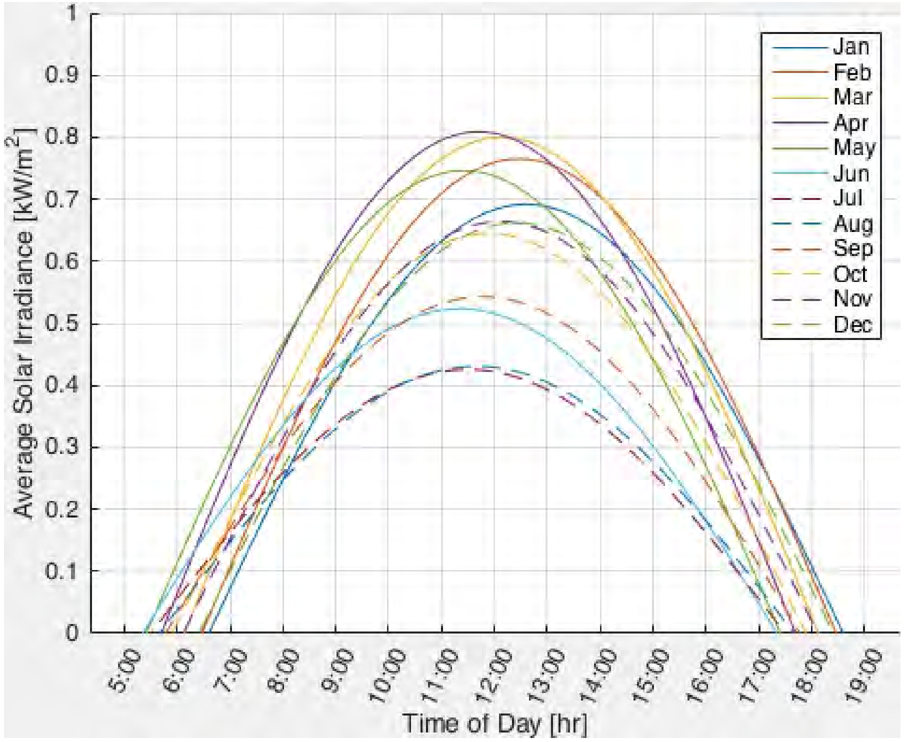

Figure 63: Average Solar Irradiance in Each Month

The highest irradiance is seen in April and March (the summer months of the region), whereas the lowest values can be seen in July and August (during the monsoon season). Having the information on the average amount of solar energy in the reservoir region throughout the year is crucial in successfully evaluating any solar powered boat designs and how much power they will be able to produce and use.

7.3.2 NavAlt Design

In an effort to implement the optimal solar ambulance design in the reservoir, the SELCO Foundation has partnered with NavAlt (which itself is a collaboration between Navgathi Marine Design & Construction Pvt. Ltd. (India), AltEn Systems (France) and EVE Systems (France)), who specializes in the design and manufacture of solar powered watercraft in India.

Throughout the design process, two variations were proposed and both will be presented as follows. The basic parameters of these designs are shown in Table 27 with the differences in design 2 highlighted in yellow.

Parameter	Design 1	Design 2
General Parameters		
Length	7.0 [m]	9.0 [m]
Breadth$_{max}$	3.0 [m]	3.0 [m]
Depth	1.1 [m]	1.1 [m]
Draught	0.6 [m]	0.6 [m]
Speed	6-7 [knots]	6-7 [knots]
Railing Height	0.8 [m]	0.8 [m]
Railing Material	Aluminum	Aluminum
Hull Material	Glass Reinforced Plastic (GRP)	Glass Reinforced Plastic (GRP)
Capacity	6 passengers	6 passengers
Electrical Components		
Number of Propulsion Motors	2	2
Propulsion Motor Rated Power	5 [kW]	5 [kW]
Propulsion Motor Rated Voltage	32 [V]	48 [V]
Propulsion Motor Efficiency	92%	92%
Number of Batteries in Bank	2	2
Battery Bank Rated Capacity	7 [kWh]	10 [kWh]
Battery Bank Maximum Depth of Discharge (DoD)	80%	80%
Battery Bank C-rate	0.45	0.45
Solar Array Rated Power	4 [kW]	5 [kW]
Diesel Generator Rated Power	7.5 [KVA]	7.5 [KVA]
Propeller & Rudder Systems		
Number of Rudders	1	1
Type of Rudder	Spade	Spade
Rudder Angle of Movement	35^o	35^o
Number of Propellors	2	2
Propellor Type	Fixed Pitch Open Screw	Fixed Pitch Open Screw
Propellor Material	Gun Metal	Gun Metal
Propellor Diameter	<70% of Full Load Draft	<70% of Full Load Draft
Number of Propellor Shafts	2	2
Propellor Shaft Material	Steel	Steel

Table 27: NavAlt Solar Boat Ambulance Design Characteristics

It has been stated from NavAlt that when the dual motor system of design 2 is running at a total of 6 kW (i.e. 3 kW to each motor) the boat will be able to travel at 6 knots, and if it is running at total of 10 kW (i.e. 5 kW to each motor) it will be able to travel at a maximum speed of 7 knots. It was assumed the same motor output would provide the same speeds for design 1 as well. This is summarized in Table 28.

Power to Each Motor [kW]	Total Power [kW]	Traveling Velocity [knots]	Traveling Velocity [$\frac{km}{hr}$]
3	6	6	11.11
5	10	7	12.96

Table 28: NavAlt Solar Boat Ambulance Traveling Velocities

The components that will be placed in the navigation room are the same for both designs 1 & 2 and are listed out in Table 29.

Item	Quantity
Pilot Chair	1
Steering Wheel & Accessories	1
Remote Control for Propulsion Motors	1
Maneuvering Desk with Navigational Code	1
Electric Horn	1
Switches and Console for Navigational Lights & Search Lights	1
Console & Instrumentation for Solar Charge Controller	1

Table 29: Items in the Navigational Room of the NavAlt Solar Ambulance Design

The proposed medical equipment that NavAlt will also provide with both designs of the boat ambulance are listed in Table 30.

Item	Quantity
Portable Suction Apparatus	1
Portable & Fixed Oxygen Equipment with Key Wrench & Trolley	1
Nebulizer	1
Glucometer	1
BP Apparatus	1
Ambu Bag	1
ECG	1
Portabel Laboratory (accuster)	1
First Aid Kit (Including Medicines for Maternal Emergency)	1
Main Stretcher/ Under Carriage	1
Transfer Mattress/ Carrying Sheet	1
Mouth to Mask Ventilator with Oxygen Inlet	1
Infusion Mounting Stand	1
Bedding Equipment	Unknown
Material for Treatment of Wounds	Unknown
Kidney Bowl	1
Vomiting Bags	Unknown

Table 30: Medical Equipment Onboard the NavAlt Solar Ambulance Design

Drawings of design 1 can be seen in Figures 64 to 66. The figures show views of the design from different orientations as well as the main deck and below main deck plans as specified.

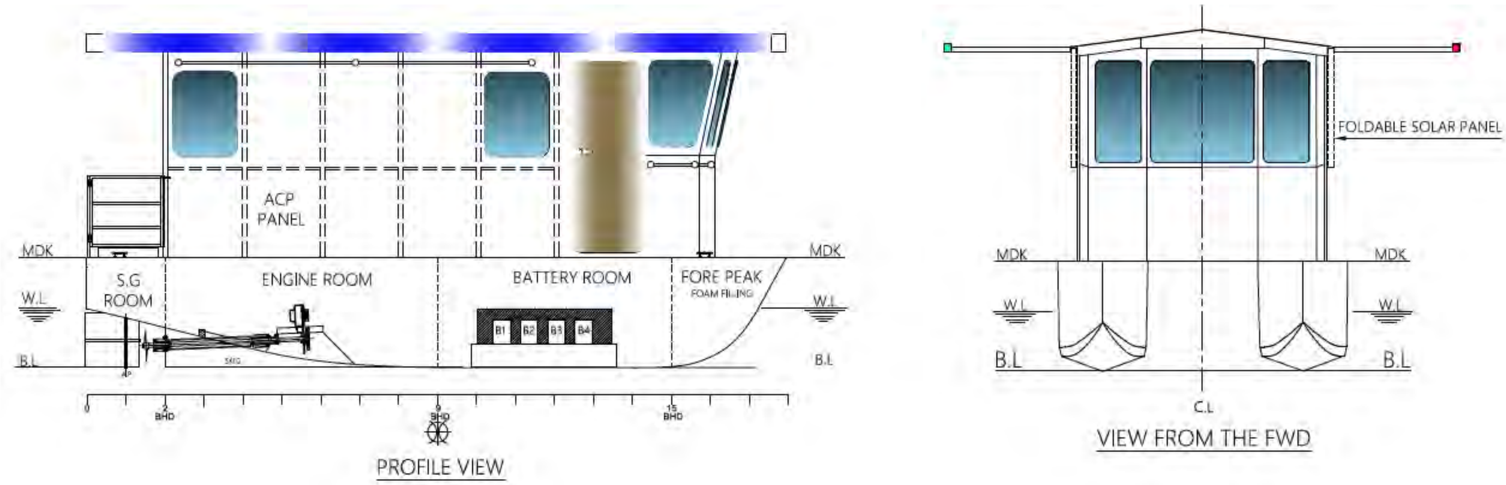

Figure 64: NavAlt Design 1 - Profile and Forward View

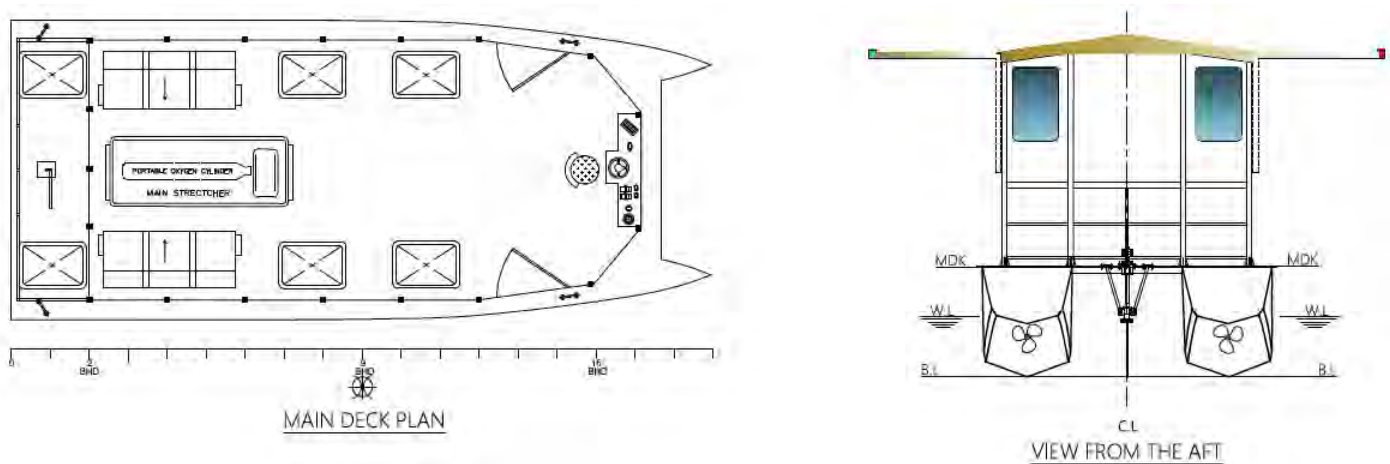

Figure 65: NavAlt Design 1 - Main Deck Plan and Aft View

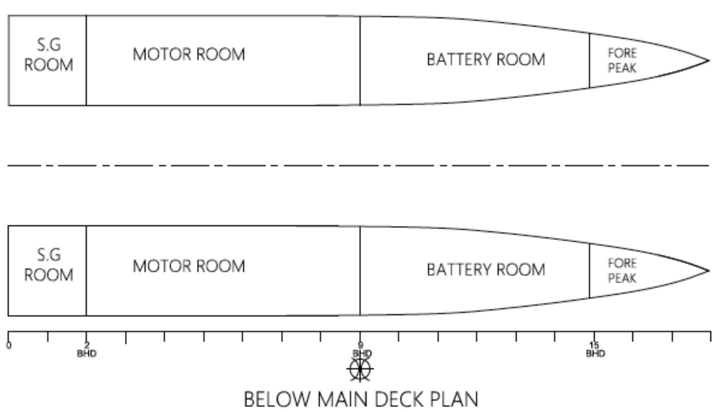

Figure 66: NavAlt Design 1 - Below Main Deck Plan[35]

The dimensions of design 2 would be very similar except longer and with a larger rooftop solar array, as detailed in Table 27.

[35] *SG Room* stands for *Steering Gear Room*

7.3.2.1 Technical Analysis

Considering the parameters of the designs listed in Section 7.3.2 and knowing the running conditions the boat ambulance will need to operate under will be equivalent to that for the current kerosene powered boat in Section 7.2.2, it is possible to carry out a technical analysis of the NavAlt proposals to ensure they will perform as required.

The electrical components of the designs are set up in such a way that the the motors can only be powered through the onboard battery banks. Therefore it is crucial to know the maximum amount of energy that is actually available for use in the battery banks. This can be calculated via equation 7

$$E_{Bat} = E_{Bat_{rated}} Bat_{DoD} N_{bat} \tag{7}$$

Where:

- E_{Bat} is the maximum amount of available energy in the battery banks of the design
- $E_{Bat_{rated}}$ is the rated capacity of each battery bank
- Bat_{DoD} is the maximum depth of discharge of the battery bank (given as 80% for both designs)
- N_{bat} is the number of battery banks in the design (given as 2 for both designs)

Considering the velocity profiles detailed in Table 28 and the efficiency of the motors, it is possible to calculate the actual power requirements of the propulsion system via equation 8

$$P_{req} = \frac{N_m P_m}{\eta_{inv} \eta_m pf} \tag{8}$$

Where:

- P_{req} is the required power that needs to be supplied to the motors for the given speed [kW]
- P_m is the rated motor power [kW] (as either 6 or 10 kW for these designs).
- N_m is the number of motors (given as 2 for both designs)
- η_{inv} is the efficiency of the inverter used (given as 90% for both designs)
- η_m is the efficiency of the motors (given as 92% for both designs)
- pf is the dimensionless power factor (assumed to be 0.80 for both designs)

With this P_{req} equation, it is possible to then determine the total amount of energy needed to travel a set distance at a specified speed using equation 9

$$E_{req} = \frac{P_{req} d}{v} \tag{9}$$

Where:

- E_{req} is the amount of energy required for the trip [kWh]
- P_{req} is the required supply power for the given speed [kW]
- d is the distance the vessel needs to travel [km]
- v is the velocity that the boat is traveling [$\frac{km}{hr}$]

By rearranging this equation to solve for distance and plugging in the maximum energy available in a fully charged battery bank as calculated in equation 7, the maximum travel distance for the different speeds can be calculated via:

$$d_{max} = \frac{E_{Bat} v}{P_{req}} \tag{10}$$

Where:

- d_{max} is the maximum distance the vessel can travel with the given battery bank and speed [km]
- E_{Bat} is the maximum amount of available energy in the battery banks of the design
- v is the velocity that the boat is traveling [$\frac{km}{hr}$]
- P_{req} is the required supply power for the given speed [kW]
- P_m is the rated motor power [kW] (either 6 or 10 kW).

Therefore with all of this information, the maximum distance that the boat can travel on one charge (assuming no input from the solar array [i.e. no charging]) is shown in Table 31

Operating Speed [knots]	Maximum Travel Distance[36] [km]	Maximum Run Time [$minutes$]
6	9.0437	48.83
7	6.3306	29.30

Table 31: Maximum Travel Distance on 1 Charge (Worst Case Scenario)

The use of these formulas in the calculation process can be seen in Appendix 8. The C-rate of the batteries is given as 0.45, meaning it will take roughly 2 hours & 15 minutes to charge completely assuming there is an adequate power supply to the battery. Therefore to cover the roughly 20 km of travel per day that is required of the vessel, it will need to recharge roughly 2.5 times a day (assuming roughly equally operation at the two different speeds) for a total charging time of 5.6 hours a day.

The battery is rated to 2,000 cycles in its lifetime, therefore the battery will exceed this amount in roughly 800 days of operation. Considering the boat will operate 5 days a week, this means the battery will operate as specified for 1,120 days from its first day of operation (3.07 years). After that point, the battery will need maintenance or need to be replaced. It has been assumed that the batteries will be used past their rated cycle life, to roughly 4 years of operation.

MATLAB & Simulink Modeling

After compiling these initial calculations, it was necessary to utilize some tools to accurately model how the boat ambulance designs would operate in the field. In order to accomplish this, a MATLAB script and associated Simulink model were used.

MATLAB is a programming software and language that allows matrix manipulations, data processing and logging, user interfacing, among many other useful tools. Simulink is a package of the MATLAB software which uses graphical models and solvers to simulate and solve different dynamic systems [73, 74].

To begin, the MATLAB code[37] prompts the user to enter the distance the boat must travel, the state of charge (SOC) at the beginning of the trip, the month of the year, and the time the trip will begin. This prompt can be seen in Figure 67.

[36]This is a worst case scenario assuming there is no charging whatsoever from the solar array. It is also assuming the boat was fully charged (SOC=100%) at the start of the trip

[37]which can be seen in Appendix 8

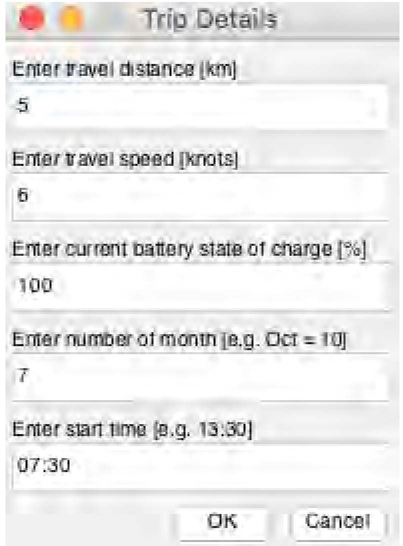

Figure 67: MATLAB Boat Ambulance Trip Details

With this information the solar irradiance data throughout the trip is calculated as detailed in Section 7.3.1 and the time and power variables are calculated as shown in Section 7.3.2.1. The code then plots the average solar irradiance for the month selected by the user, highlighting the area under the curve that matches with the time required to complete the trip[38]. An example of this can be seen in Figure 68.

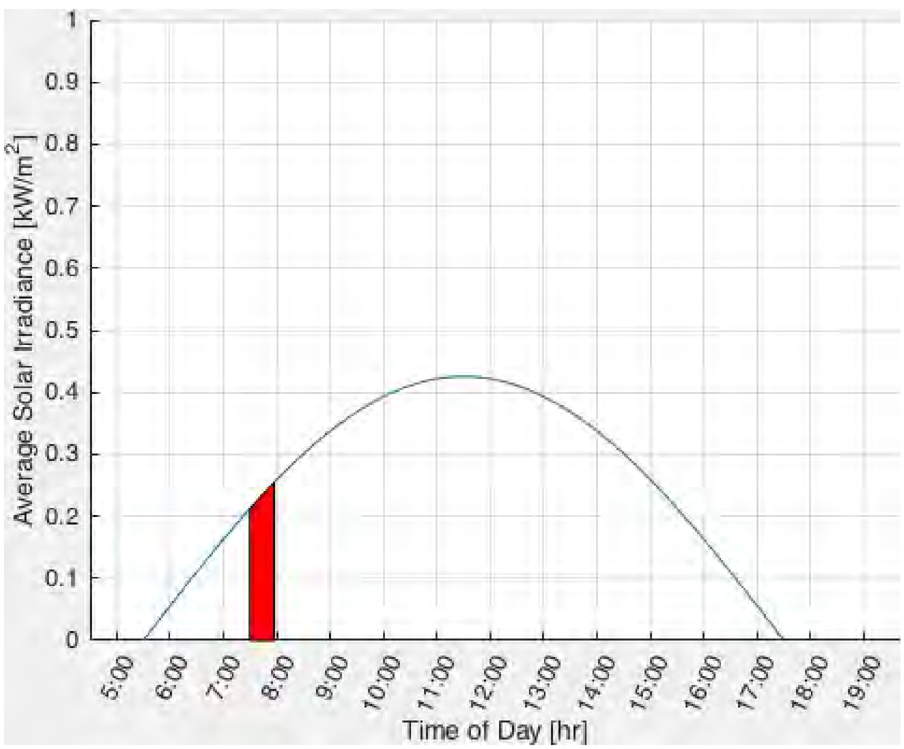

Figure 68: Average Solar Irradiance in Selected Month[39]

The data calculated in the MATLAB code is then exported to a Simulink model which has been created to represent the boat ambulance. In order to simplify the model, symmetry was assumed, and only one battery bank and one motor were modeled. An overview of the model is shown in Figure 69.

[38]The trip time is calculated assuming the boat is able to run continuously throughout the trip
[39]July was the selected month for this image.

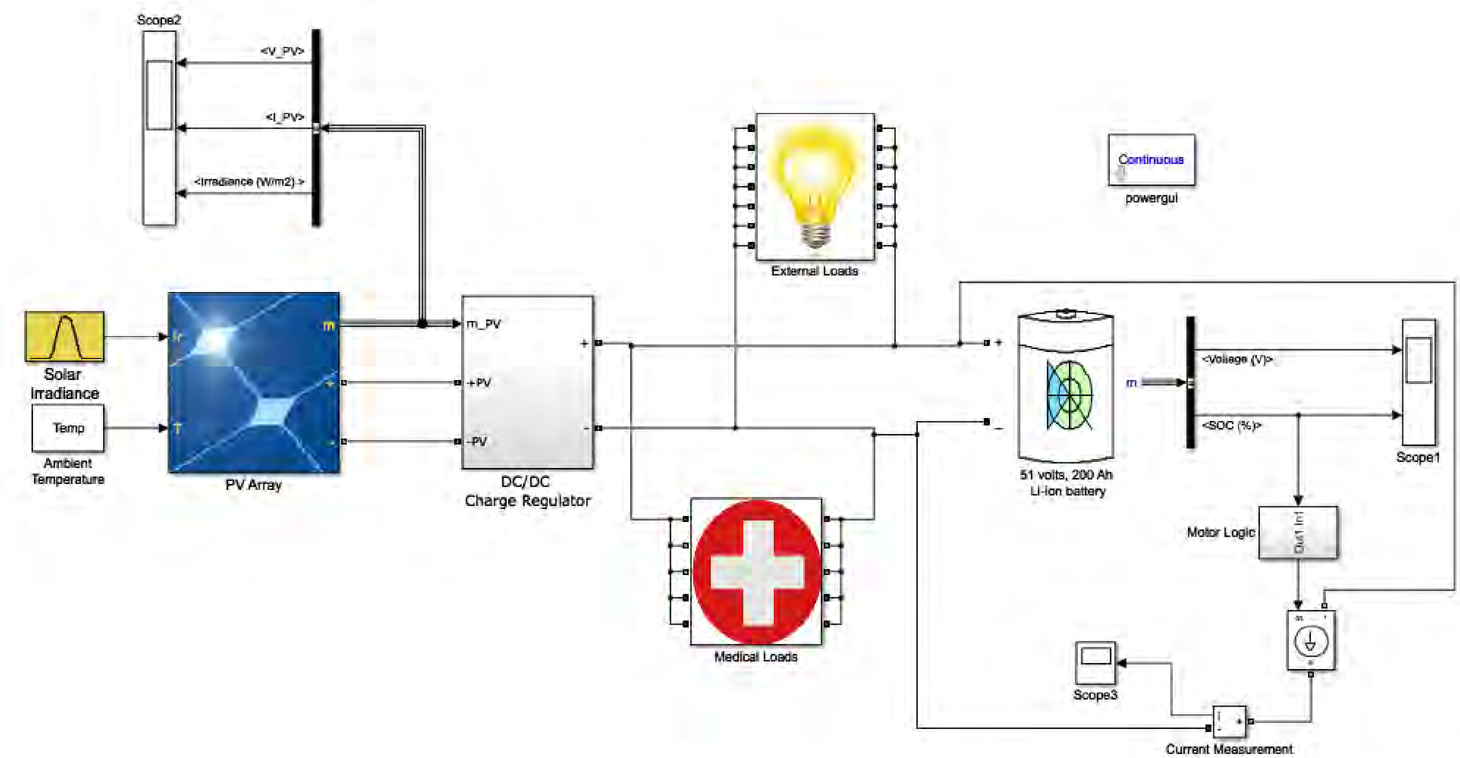

Figure 69: Boat Ambulance Simulink Model[40]

Variables that have been generated in the script are substituted into each of the subsystems shown. The model imports the temperature and solar irradiation data for the given month and time period of the trip that the user has entered. This information is passed into a model for the solar array of the boat to determine how much power will be produced throughout the duration of the trip. This power produced is fed into a charge regulator which then supplies the battery bank. The loads connected to the battery are split into the medical loads, the electrical loads, and the driving motors. All loads are modeled as constant current sinks whose values have been calculated in the MATLAB script in Appendix 8.

The loads are all pulse source based, meaning they will continually switch on and off for set durations over the course of the trip. This was done in an effort to simulate how the loads would really be operated in the field. Examples of how these loads were set up for the external and medical components can be seen in Figure 70 and Figure 71.

[40]The model shown represents values of Design 2 from NavAlt

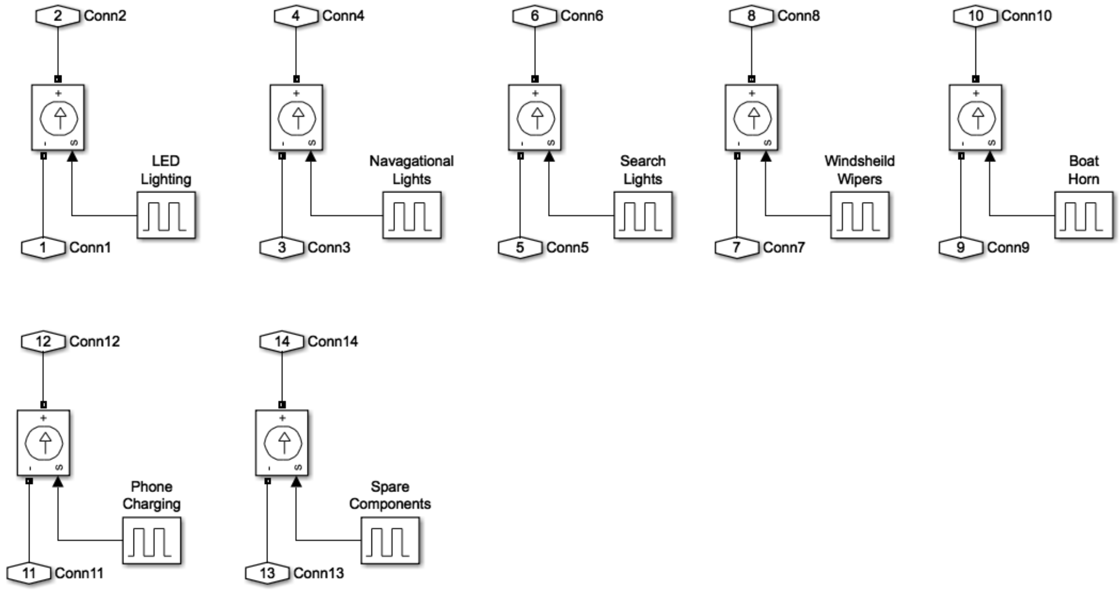

Figure 70: Simulink External Load Modeling

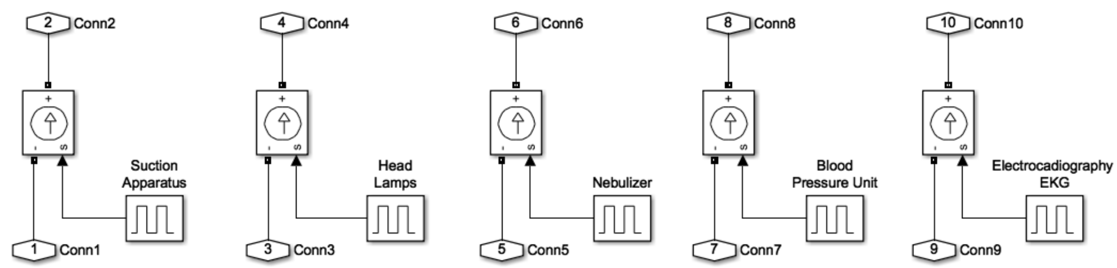

Figure 71: Simulink Medical Load Modeling

In order to operate the motor appropriately, a logic subsystem had to be developed. This subsystem monitors the state of charge of the battery bank, and when the battery bank reaches its maximum depth of discharge (i.e. 20% SOC), the relay turns off the motor until the solar charging brings the State of Charge (SOC) back to a preset level (this was set to be 60%). Ideally this recharging would take place while the boat ambulance is docked at one of the villages of the reservoir. If not the boat would have to wait in the water to charge, or a backup generator could be used to produce the required electricity. This motor logic is shown in Figure 72.

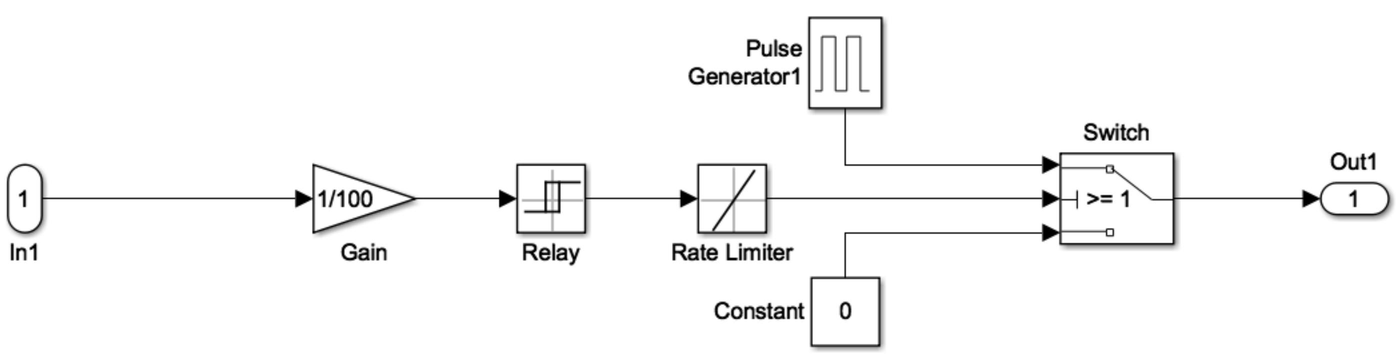

Figure 72: Simulink Motor Logic Modeling

This model was utilized to calculate the performance of Nav Alt design 2, in a simulation where the boat left during the month with the worst solar irradiance as detailed in Figure 67 and Figure 68: a 5 km journey, traveling at 6 knots, in July, beginning at 7:30am, beginning with 100% charge. This trip amounts to a 45 minute ride through the reservoir for the given speed and distance. July was chosen because it has the lowest irradiation values for the region and could serve as a worst case example to determine if the design would meet the requirements of the application. The details of the PV arrays voltage, amperage, and the irradiance on the system throughout the trip are shown in Figure 73.

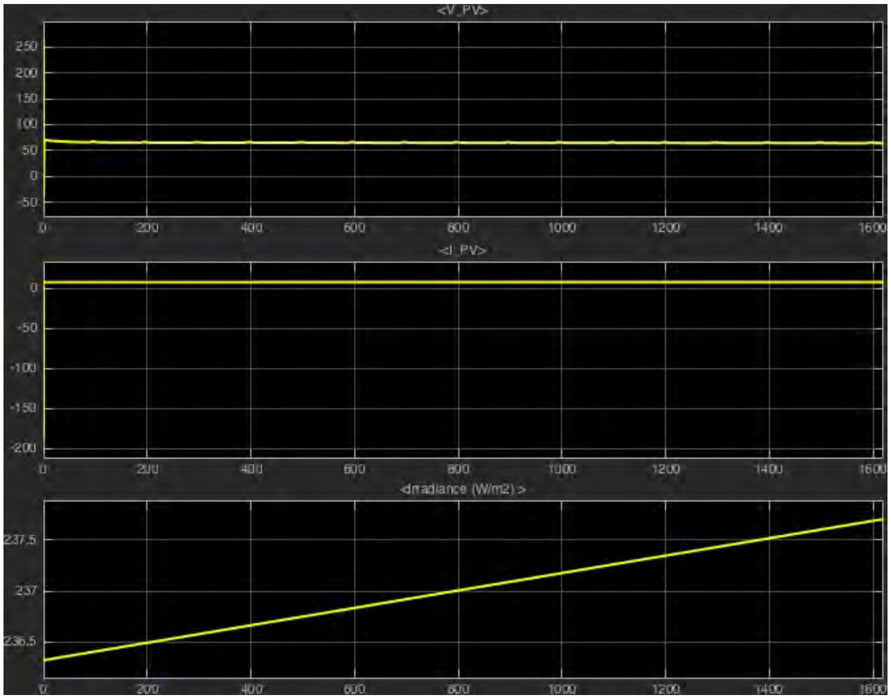

Figure 73: Simulink Modeling of PV Generation for 5km Trip in July

These values, along with the motor usage throughout the trip shown in Figure 74 provide the basis of calculating the SOC and voltage of the battery bank throughout the trip, as shown in Figure 75.

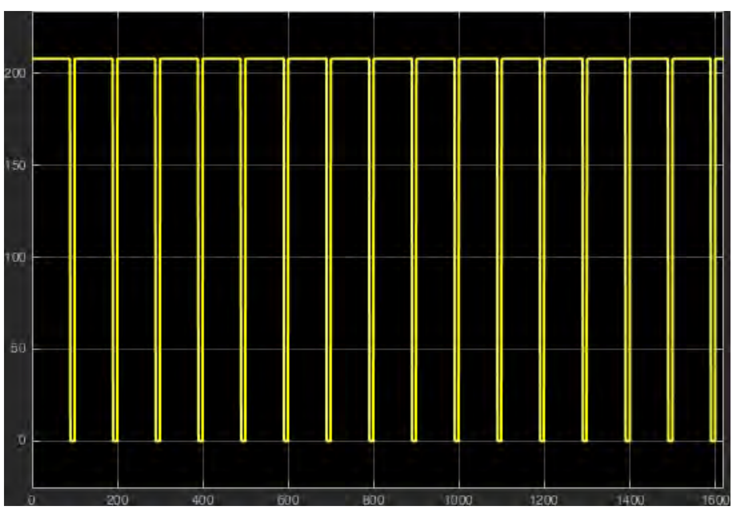

Figure 74: Simulink Modeling of Motor Usage for 5km Trip in July

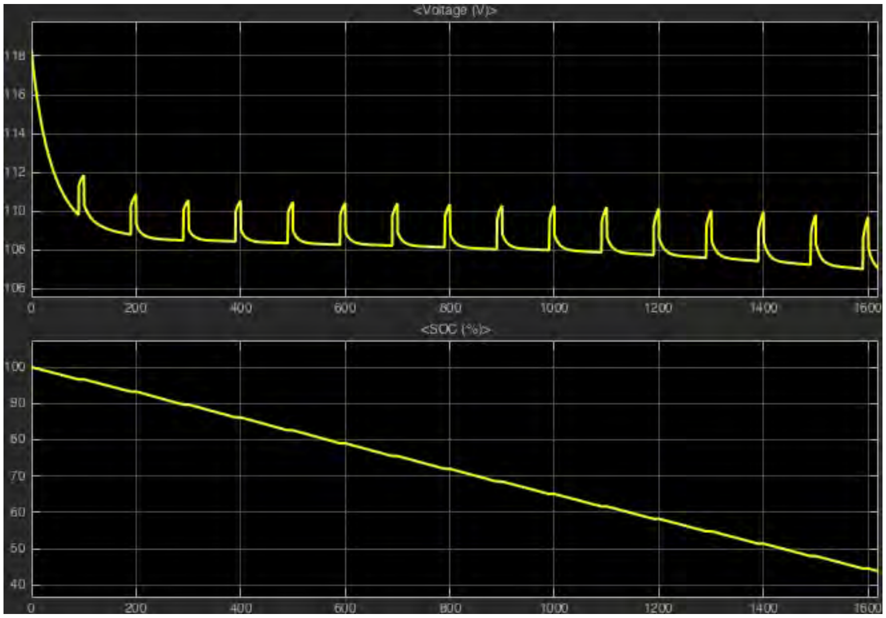

Figure 75: Simulink Modeling of Battery Bank for 5km Trip in July

This trip drained nearly 60% of the battery bank's charge. Had it been a different time of the year, this value would have been less as the solar system would have been able to supplement this power requirement at a higher rate.

The pulsing nature of the loads is evident when examining at the voltage of the battery over time, as well as the motor usage.

Another test was run which started at sunrise on a July day and ran indefinitely, the purpose of which was to see how long the boat could potential travel, and therefore how far it could reach in a day, during the worst month. The simulation was able to run for roughly 7,250 seconds (2 hours). Figure 76 shows how the SOC of the battery varies throughout the trip.

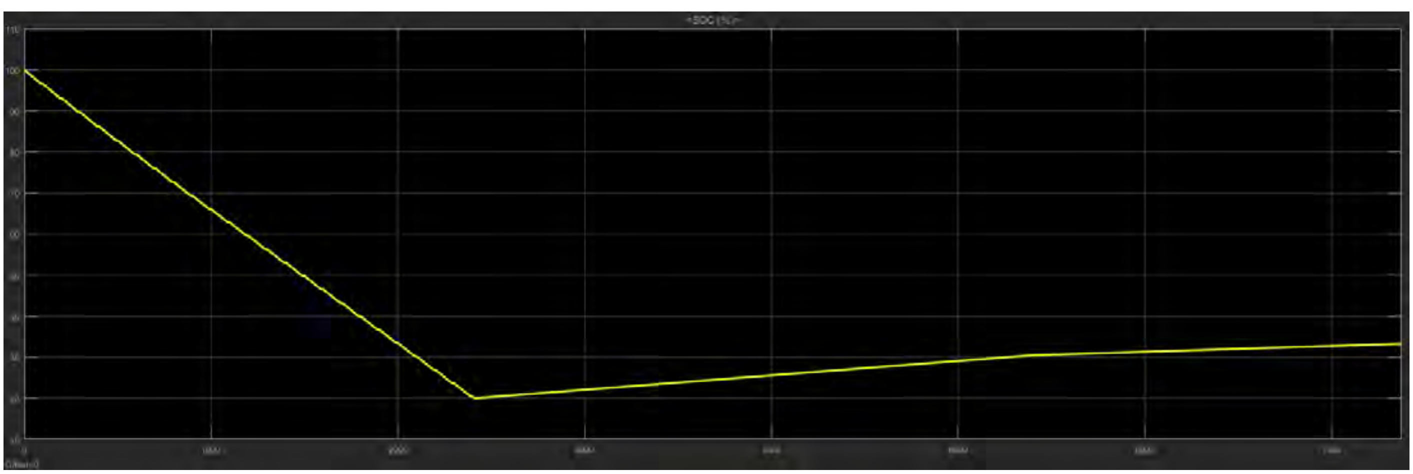

Figure 76: Simulink Modeling of Battery Bank for July

The motor and load usage drains the battery in about 40 minutes of running time. After this point, the rest of the trip is an effort to recharge the batteries, and over the next 1 hour and 20 minutes the battery is only able to charge roughly 13% to reach a 33% SOC. As can be seen in Figure 77 the irradiance is very low throughout the trip.

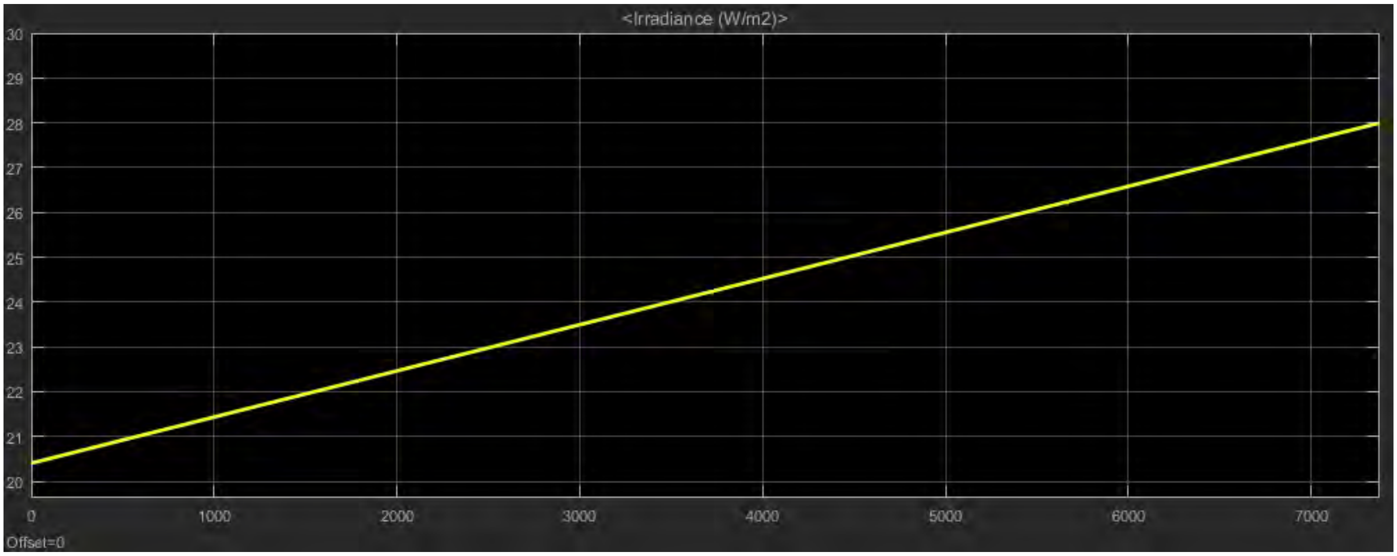

Figure 77: Simulink Modeling of Solar Irradiance for July

This is due to the fact of the trip taking place during the worst month, and in the very early morning, when there is not much solar resource.

The resulting PV voltage and current throughout this process can be seen in Figures 78 and 79 respectively

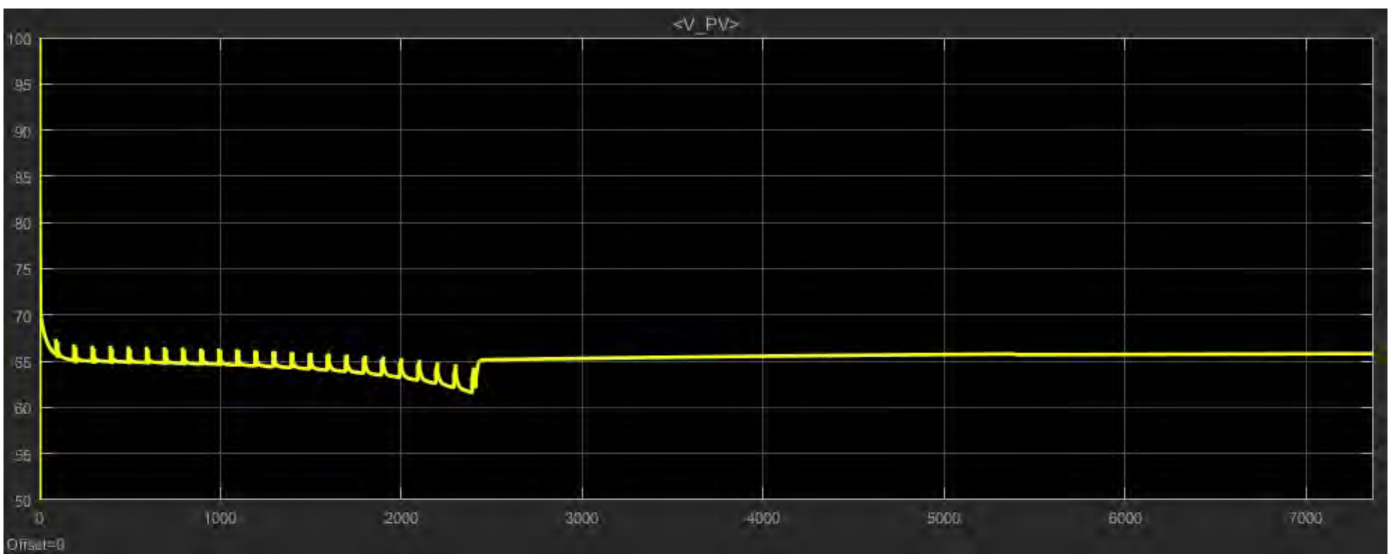

Figure 78: Simulink Modeling of Solar PV Voltage for July

The PV voltage oscillates as the loads change throughout the run time, however once they are shut off, the voltage stabilizes.

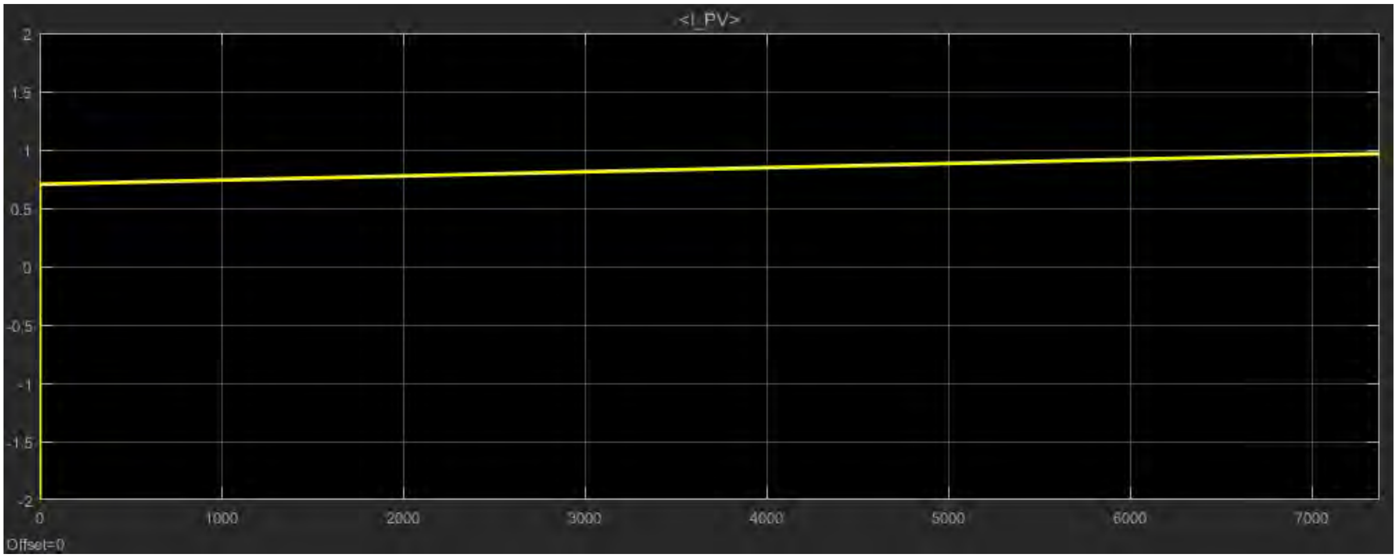

Figure 79: Simulink Modeling of Solar PV Current for July

The PV current slightly increases throughout the length of the run. The current draw of the propulsion motor through the trip can be seen in Figure 80

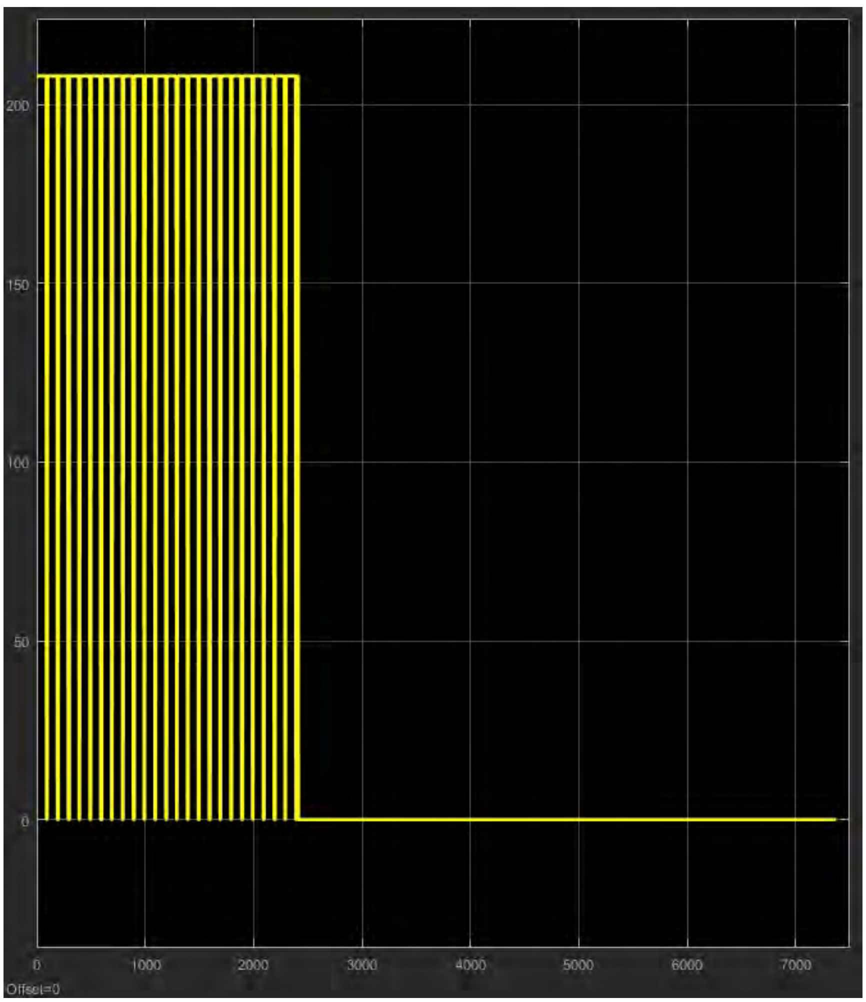

Figure 80: Simulink Modeling of Motor Current for July

As shown, there are several oscillations of the motor current throughout its run time, as was predefined. Once the

SOC reaches 20%, the motor turns off and it's current draw drops to 0A. A zoomed in view of this motor current draw can be seen in Figure 81.

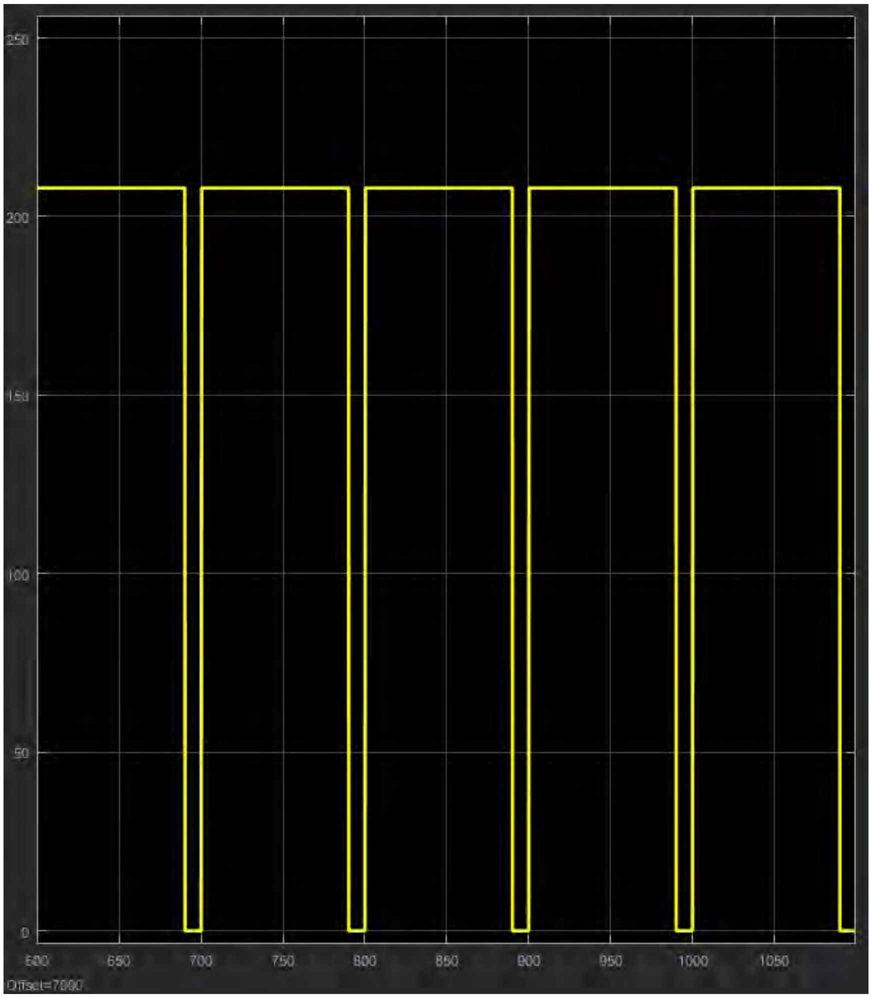

Figure 81: Simulink Modeling of Motor Current for July: Zoomed View

This oscillating motor draw results in similar variations in the voltage of the battery bank, as shown in Figure 82.

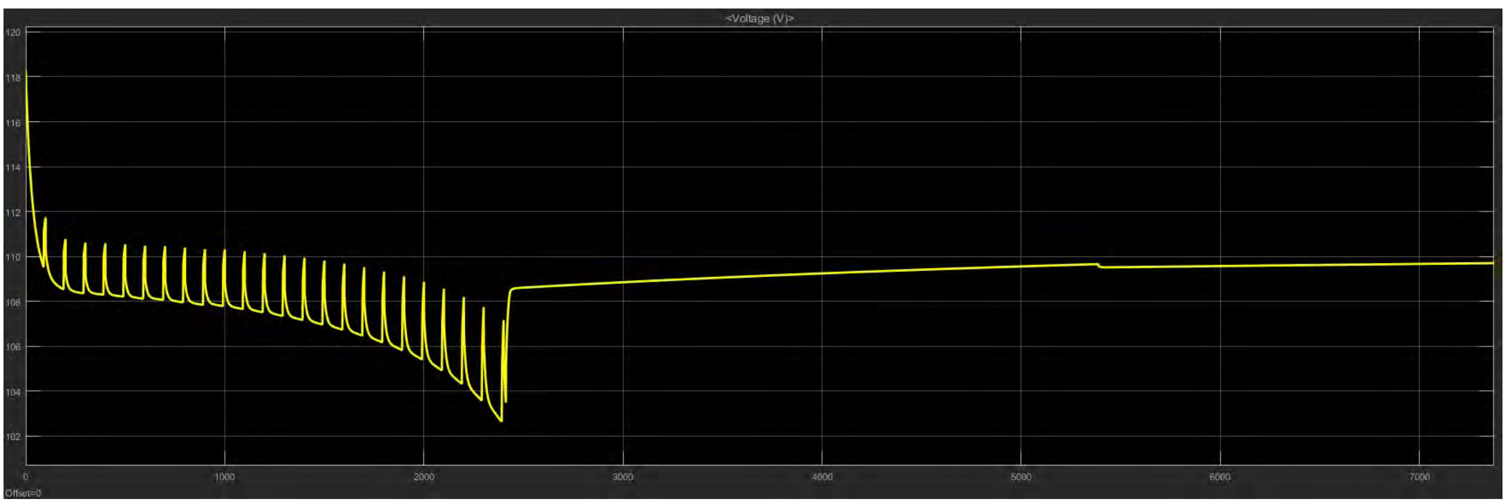

Figure 82: Simulink Modeling of Battery Voltage for July

The batteries voltage continues to drop as the SOC does, until finally the motor is switched off, and the voltage begins to stabilize and increase once there is only the input from the PV array in the system.

With this information it can be inferred that as a conservative estimate it would take roughly 4 hours to reach the 60% SOC required for the motor to be in operation again[41]. Therefore, the boat would be able to travel for three full 45 minute runs. At a speed of 6 knots, this equates to roughly 25 km of travel on an average July day. This puts the operation of the boat within the requirements of OVHA.

In addition to the Simulink model, calculations were done by hand utilizing the equations in Section7.3.2.1. These values reinforce the estimations that have been extracted from the Simulink model. The calculated maximum travel time for a given month of the year, depending on the starting SOC can be seen in Figures 83 and 84

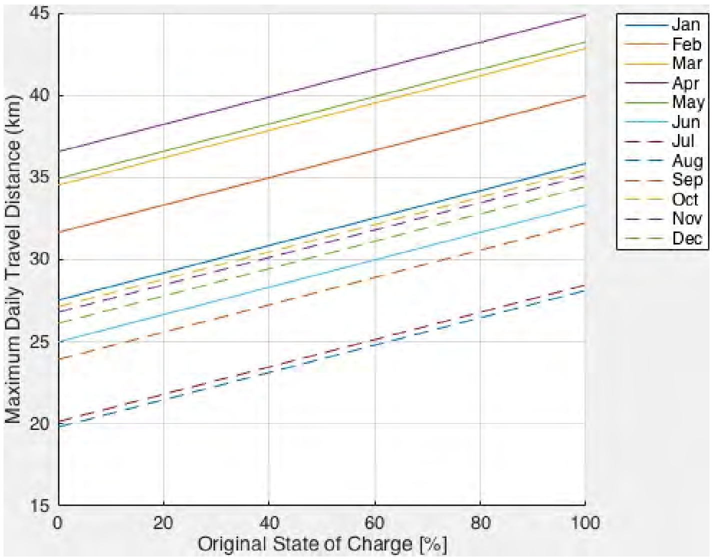

Figure 83: Max Travel Distance vs. SOC at 6 knots

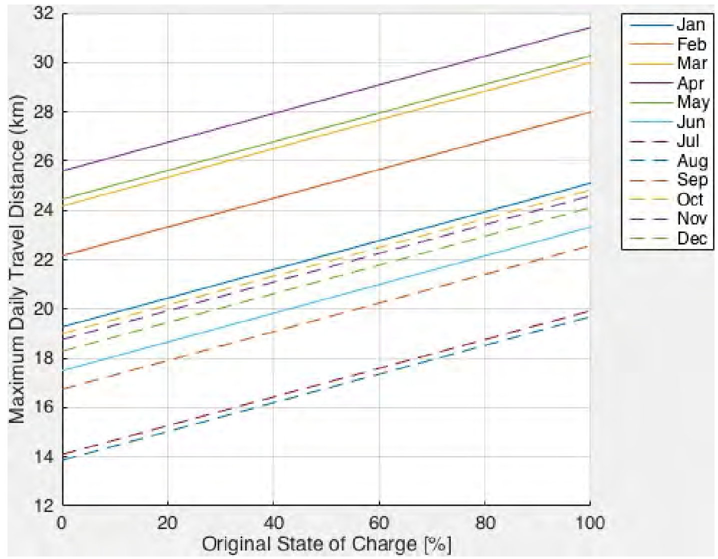

Figure 84: Max Travel Distance vs. SOC at 7 knots

As can be seen, a boat traveling at 6 knots in July, beginning with a 100% SOC could travel for roughly 27 km in a day (slightly more than the conservative estimate from the Simulink model).

Lessons Learned from MATLAB & Simulink Modeling

The use of the MATLAB and Simulink software was very informative in determining if the boat ambulance would be able to function as needed in the application. Based on the results from the July run it can be inferred that design 2 would meet the requirements laid out by OVHA, even in the worst month of the year with regards to solar irradiation. However the trips would need to be planned carefully during this time of year to ensure the operators have enough charge to reach their destinations and return.

Unfortunately this simulation took up a very significant amount of processing power and time due to the way the charge regulator was designed in the model. Therefore only 2 hours of the day could be simulated. The code and software had to be sent to another more powerful machine for processing, and even still it took several hours to do so. Moving forward, this simulation will need to be refined and made more efficient to be of real use in planning and mapping out the possible trips of one of the Nav Alt designs.

[41] This is a conservative estimate because it is assuming the same charging rate as shown in Figure 76, which would increase throughout the day in reality.

7.3.2.2 Financial Analysis

Design 1 from Navgathi was original quoted at 47.5 lakh[42] ₹, while design 2 rose to 59.5 lakh ₹. To determine if one design was better than the other, or if either were feasible, a financial analysis was needed.

The current operating and maintenance costs of the kerosene powered boat ambulance were provided by OVHA. These values were used to estimate the operational and maintenance costs that would be associated with the NavAlt design for future financial calculations. It was estimated that they would be 10% and 25% of the values for the kerosene boat respectively. These values and estimations can be seen in Table 32.

Type of Boat	Type of Costs	Value [$\frac{INR}{Day}$]
Kerosene	Operational Costs	300 - 450 $\frac{INR}{Day}$
	Maintenance Costs	1500 $\frac{INR}{Month}$
NavAlt Solar Electric	Operational Costs	30 - 45 $\frac{INR}{Day}$
	Maintenance Costs	375 $\frac{INR}{Month}$

Table 32: Boat Ambulance Operation & Maintenance Costs

The life of the kerosene outboard motor was estimated to be roughly equivalent to that of a gasoline powered outboard motor. Gasoline powered outboard motors can run for roughly 1,500 hours before needing major overhaul or replacement [75]. Using the operational parameters described in Section 7.2.2, it can be calculated that the kerosene boat will have roughly 180 operational hours every year. Therefore the motor will need to be replaced every 8.3 years. The current design is using a Yamaha Enduro Kerosene EK25B motor, which can be found for 2.078 lakh ₹[76].

Lithium ion batteries have an average price of roughly 350 $\frac{USD}{kWh}$ or 22,550 $\frac{INR}{kWh}$ and for the sake of this model they were assumed to have a lifespan of roughly four years [77]. Therefore a new 7.5 kWh battery pack at the conclusion of four years, such as in design 1 could cost roughly 1.7 lakh ₹. In design 2 this could cost 2.25 lakh ₹every four years. With improvements in battery technology in the coming years, it can be almost guaranteed that the price of Li-ion batteries will drop, and the cycle life will increase, however as a worst case scenario, this value can be assumed to be a reoccurring set cost every four years. The net present value of the rupee should also be taken into account, and how its value will alter over time, including the effects of inflation, but to keep the analysis straightforward a simple payback period was calculated and is represented in Figure 85.

[42] 1 lakh = 100,000

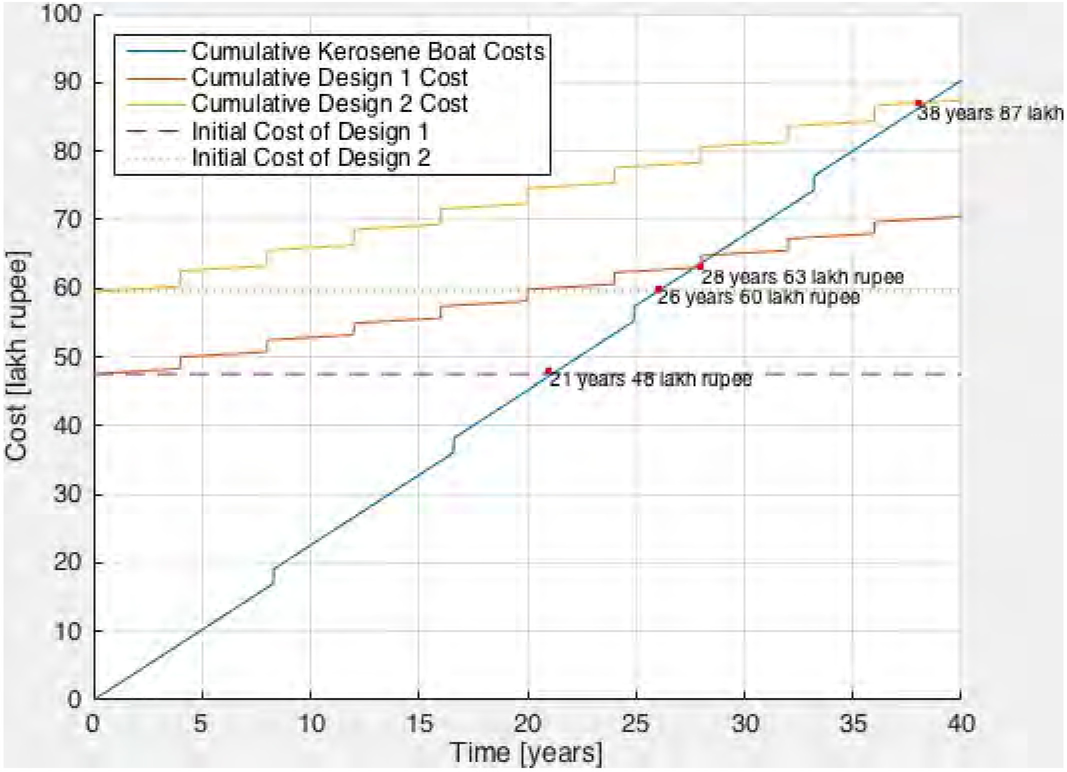

Figure 85: Boat Ambulance Cost Over Time

The cumulative kerosene boat costs include the current operation and maintenance of the boat, and factor in the cost associated if the boat were able to operate for the average week of each month that it does not have fuel, as described in Section 7.2.2. As can be seen, assuming the purchases of a new battery system every four years at the current price per unit energy, it will take 28 years for design 1 to match the cost of running the kerosene powered boat and 38 years for design 2. As a reference, the initial costs of both of the NavAlt designs have been shown as well. It will take 21 years for the cost of the running kerosene ambulance to reach this value.

This financial analysis however does not take into account if there is an increase or decrease in the range of the solar powered boat ambulance versus the kerosene boat. Therefore it does not associate a monetary value to the amount of villages visited or patients seen.

7.4 Moving Forward

In conclusion, design 2 in particular from NavAlt would be sufficient in carrying out the duties of the current kerosene powered boat ambulance, and will have more freedom of operation since it will not be constricted by the necessity of having fuel on-site. The operating parameters of the design have been discussed with OVHA and are acceptable for their requirements. This design will offer a larger number of inhabitants of the Indravati Power Station Reservoir medical treatment, information, and access to the primary health center in Adri. As stated, the added benefits of this increase in patient size and outreach have not been factored economically into the financial analysis.

However, both designs from NavAlt have high initial prices, and the simple economic breakeven point of the investment, when compared to the current operating costs of the kerosene powered ambulance, will take a minimum of roughly two decades and four decades for the designs respectively. Admittedly this payback period does not include the time value of money or how the technologies used will improve in the future.

It has not been calculated or determined how much wider of a population base could be reached by the ambulance with the implementation of one of these designs in the reservoir region.

8 Conclusion

After examining the state of primary health care in the regions discussed, and analyzing the case studies presented, it has been established that through the use of solar PV technology there is clear potential to improve the primary health care available to populations living in rural and tribal areas of developing countries. Solar PV has the benefit of allowing stand alone systems in isolated areas, requiring little maintenance, and their price has been plummeting in recent years. The advancing efficiency means more power can be drawn from smaller areas, increasing the energy access to these remote places and people.

The research of these case studies has shown that implementations of solar PV systems in primary health centers brought an average of 31% savings in their monthly electricity bill. These systems also helped to combat the power outages and unreliable electricity which plagues the PHCs in question on average 18% of the time.

The study of solar direct drive vaccine refrigeration has shown that the technology is capable of keeping its contents within the required temperature range between 2^{o}C and 8^{o}C while deployed in the field. These systems are highly regarded on a consistent basis by those who work them. Based on the experiences at the PHCs in question, it is clear that proper temperature monitoring and data logging is necessary to ensure the systems are performing as required. Surveying has also shown that when implementing devices such as these, it is crucial to have the operators properly educated on how they're used and to verify that they are in fact able to use them without compromising any agreements with third parties (such as governments).

The analysis of the solar powered boat ambulance has shown that a design such as this can provide a reliable means to bridge the geographic divide between tribal communities and the health care they require. The specific design in question was shown to be adequate in covering the distance range required to treat all of the inhabitants of the reservoir region, even during the monsoon season of the year. It was able to meet the minimum requirement of 20 km of travel per day, and considering the availability of a backup electric generator, the design would be able to bring medicines and health professionals to where they are needed, and to ferry patients to the nearest PHC when required.

As discussed, solar PV has the potential to power a large share of PHC's energy demands. It can also be used to store life savings and temperature sensitive vaccines in the places where they are needed and most at risk of deviating from their temperature zones. Solar PV also has the potential to facilitate more geographic accessibility to the communities that live in these hard to reach places of the world, and can help provide them with life saving medical care that they are currently lacking.

Different projects around the world will require specific analyzes to determine if the use of solar PV is viable and economically feasible. However as time goes on, it seems their use will be more widespread and potentially offer a means to better health for millions around the globe.

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Appendices

MATLAB Code

PHC Grid Electricity Data

```
%% PHC Data Graphing
%Opening Excel data
clc
clear
close all
filename = 'PHC_Electricity.xlsx';
sheet = 1;

%% Plotting for Hudem
xlRange = 'A8:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'B8:B23'; %Range for SRR Pura electric bill
xl2Range = 'K8:K23'; %Range for SRR Pura energy consumption
Hudem_Bill = xlsread(filename,sheet,xlRange);
Hudem_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
grid on
grid minor
%title('Hudem Electricity Prices and Energy Usage')
xlabel('Date','fontsize',13) % x-axis label

set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, Hudem_Bill, Date, Hudem_kWh);
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(12) Date(12)],y1,'r')
hFig = figure(1);
set(hFig, 'Position', [0 500 1350 500])
export_fig Hudem_Price.jpg

%% Plotting for SRR Pura
xlRange = 'A7:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'C7:C23'; %Range for SRR Pura electric bill
xl2Range = 'L7:L23'; %Range for SRR Pura energy consumption
SRR_Pura_Bill = xlsread(filename,sheet,xlRange);
SRR_Pura_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
```

```
grid on
grid minor
%title('SRR Pura Electricity Prices and Energy Usage')
xlabel('Date','fontsize',13) % x-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, SRR_Pura_Bill, Date, SRR_Pura_kWh);
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(13) Date(13)],y1,'r')
hFig = figure(2);
set(hFig, 'Position', [0 500 1350 500])
export_fig SRR_Pura_Price.jpg

%% Plotting for Anegundi
xlRange = 'A8:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'D8:D23'; %Range for Anegundi electric bill
xl2Range = 'M8:M23'; %Range for Anegundi energy consumption
Anegundi_Bill = xlsread(filename,sheet,xlRange);
Anegundi_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
grid on
grid minor
title('Anegundi Electricity Prices and Energy Usage')
xlabel('Date','fontsize',13) % x-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, Anegundi_Bill, Date, Anegundi_kWh);
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(11) Date(11)],y1,'r')
hFig = figure(3);
set(hFig, 'Position', [0 500 1350 500])
export_fig Anegundi_Price.jpg

%% Plotting for Gumballi
xlRange = 'A7:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'E7:E23'; %Range for Gumballi electric bill
xl2Range = 'N7:N23'; %Range for Gumballi energy consumption
Gumballi_Bill = xlsread(filename,sheet,xlRange);
Gumballi_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
grid on
grid minor
title('Gumballi Electricity Prices and Energy Usage')
```

```
xlabel('Date','fontsize',13) % x-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, Gumballi_Bill, Date, Gumballi_kWh);
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(6) Date(6)],y1,'r')
hFig = figure(4);
set(hFig, 'Position', [0 500 1350 500])
export_fig Gumballi_Price.jpg

%% Plotting for GH Koppa
xlRange = 'A7:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'F7:F23'; %Range for GH Koppa electric bill
xl2Range = 'O7:O23'; %Range for GH Koppa energy consumption
GH_Koppa_Bill = xlsread(filename,sheet,xlRange);
GH_Koppa_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
grid on
grid minor
title('GH Koppa Electricity Prices and Energy Usage')
xlabel('Date','fontsize',13) % x-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, GH_Koppa_Bill, Date, GH_Koppa_kWh);
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(13) Date(13)],y1,'r')
hFig = figure(5);
set(hFig, 'Position', [0 500 1350 500])
export_fig GH_Koppa_Price.jpg

%% Plotting for Kannur
xlRange = 'A7:A23'; %Range for date values
Date = xlsread(filename,sheet,xlRange);
Date = datetime(Date,'ConvertFrom','excel');
xlRange = 'G7:G23'; %Range for Kannur electric bill
xl2Range = 'P7:P23'; %Range for Kannur energy consumption
Kannur_Bill = xlsread(filename,sheet,xlRange);
Kannur_kWh = xlsread(filename,sheet,xl2Range);

figure
hold on
grid on
grid minor
title('Kannur Electricity Prices and Energy Usage')
xlabel('Date','fontsize',13) % x-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
[hAx,~,~] = plotyy(Date, Kannur_Bill, Date, Kannur_kWh);
```

```
ylabel(hAx(1),'Electricity Bill [INR]','fontsize',13) % left y-axis
ylabel(hAx(2),'Energy Consumption from Grid [kWh]','fontsize',13) % right y-axis
y1=get(gca,'ylim');
plot([Date(14) Date(14)],y1,'r')
hFig = figure(6);
set(hFig, 'Position', [0 500 1350 500])
export_fig Kannur_Price.jpg

%% GH Koppa Reliability Data (March 25 - June 2 2017)
x = [0.219252857 0.741537143 0.038092857 0.001117143];
labels = {'No Supply','Normal Voltage','No Data', 'Low Voltage',};
explode = [1,0,0,0];
figure
set(0, 'defaultTextFontSize',13);
pie3(x,explode)
colormap([0.25 0.25 0.9;  % blueish
          0.25 0.9 0.25;  % greenish
          0.5 0.5 0.5;    % grey
          0.9 1 0.25])    % yellowish
legend(labels,'Location','southoutside','Orientation','horizontal','fontsize',11)
zoom(1.8)
str = 'March 25, 2017 - June 2, 2017';
dim = [.31 0 .3 .25];
annotation('textbox',dim,'String',str,'FitBoxToText','on','fontweight','bold');
%title('GH Koppa Electricity Reliability')
ax = gca;
ax.TitleFontSizeMultiplier = 1.5;
export_fig GH_Koppa_Reliability.jpg

%% Kannur Reliability Data (March 25 - September 5 2017)
x = [0.215707879 0.667350303     0.018430303     0.015030303     0.083481212];
labels = {'No Supply','Normal Voltage','No Data', 'Low Voltage', 'High Voltage'};
explode = [1,0,0,0,0];
figure
set(0, 'defaultTextFontSize',13);
pie3(x,explode)
colormap([0.25 0.25 0.9;  % blueish
          0.25 0.9 0.25;  % greenish
          0.5 0.5 0.5;    % grey
          0.9 1 0.25;     % yellowish
          0.9 0.25 0.25]) % redish
legend(labels,'Location','southoutside','Orientation','horizontal','fontsize',11)
zoom(1.8)
str = 'March 25, 2017 - September 5, 2017';
dim = [.31 0 .3 .25];
annotation('textbox',dim,'String',str,'FitBoxToText','on','fontweight','bold');
%title('Kannur Electricity Reliability')
ax = gca;
ax.TitleFontSizeMultiplier = 1.5;
export_fig Kannur_Reliability.jpg

%% Hudem Reliability Data (March 25 - June 10 2017)
x = [0.087608861 0.907525316 0.004865823];
```

```
labels = {'No Supply','Normal Voltage','Low Voltage'};
explode = [1,0,0];
figure
set(0, 'defaultTextFontSize',13);
pie3(x,explode)
colormap([0.25 0.25 0.9;  % blueish
          0.25 0.9 0.25;  % greenish
          0.9 1 0.25]);    % yellowish
legend(labels,'Location','southoutside','Orientation','horizontal','fontsize',11)
zoom(1.8)
str = 'March 25, 2017 - June 10, 2017';
dim = [.31 0 .3 .25];
annotation('textbox',dim,'String',str,'FitBoxToText','on','fontweight','bold');
%title('Hudem Electricity Reliability')
ax = gca;
ax.TitleFontSizeMultiplier = 1.5;
export_fig Hudem_Reliability.jpg

%% SRR Pura Reliability Data (March 23 - September 5 2017)
x = [0.097275449 0.853107186 0.049617365];
labels = {'No Supply','Normal Voltage','Low Voltage'};
explode = [1,0,0];
figure
set(0, 'defaultTextFontSize',13);
pie3(x,explode)
colormap([0.25 0.25 0.9;  % blueish
          0.25 0.9 0.25;  % greenish
          0.9 1 0.25]);    % yellowish
legend(labels,'Location','southoutside','Orientation','horizontal','fontsize',11)
zoom(1.8)
str = 'March 23, 2017 - September 5, 2017';
dim = [.31 0 .3 .25];
annotation('textbox',dim,'String',str,'FitBoxToText','on','fontweight','bold');
%title('SRR Pura Electricity Reliability')
ax = gca;
ax.TitleFontSizeMultiplier = 1.5;
export_fig SRR_Pura_Reliability.jpg

%% Anegundi Reliability Data (March 4 - August 25 2017)
x = [0.093624571 0.878373143 0.026660571]; % 0.001076 0.000265714];
labels = {'No Supply','Normal Voltage','No Data'}; %, 'Low Voltage', 'High Voltage'};
explode = [1,0,0]; %,0,0];
figure
set(0, 'defaultTextFontSize',13);
set(gca,'fontsize',18)
pie3(x,explode)
colormap([0.25 0.25 0.9;  % blueish
          0.25 0.9 0.25;  % greenish
          0.5 0.5 0.5]);   % grey
        % 0.9 1 0.25;     % yellowish
         %0.9 0.25 0.25]) % redish
legend(labels,'Location','southoutside','Orientation','horizontal','fontsize',11)
```

```
zoom(1.8)
str = 'March 4, 2017 - August 25, 2017';
dim = [.31 0 .3 .25];
annotation('textbox',dim,'String',str,'FitBoxToText','on','fontweight','bold');
%title('Anegundi Electricity Reliability')
ax = gca;
ax.TitleFontSizeMultiplier = 1.5;
export_fig Anegundi_Reliability.jpg
```

SureChill Testing Data

```matlab
%% SureChill Data Graphing
%Opening Excel workbook
clc
clear
close all
filename = 'SureChill_Testing_Data.xlsx';

%% Plotting 46hr Data

%Extracting Dates
sheet = 1;
xlRange = 'A2:A65536'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');


%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Plotting 46hr Temperature Data

%Extracting Temperature Data
xlRange = 'B2:B65536'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13)
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 10])
export_fig SureChill_Temp_Data.jpg

%Plotting 46hr Power Consumption Data

%Extracting Power Data

xlRange = 'E2:E65536'; %Range for SureChill power consumption data
Power = xlsread(filename,sheet,xlRange);

```

```
figure
hold on
grid on
grid minor
set(gca,'fontsize',13)
xlabel('Date')
ylabel('Solar Array Power Production [W]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Power)
xlim([L1,L2])
export_fig SureChill_Power_Data.jpg

%% Plotting Initial Cool Down

%Opening Initial Cooldown Data Dates
sheet2 = 2;
xlRange = 'A2:A3898'; %Range for date values
Date_Time2 = xlsread(filename,sheet2,xlRange);
Date_Time2 = datetime(Date_Time2,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time2(1);
x2 = Date_Time2(end);
y1 = 8;
y2 = 2;


%Extracting Temperature Data
xlRange = 'B2:B3898'; %Range for SureChill temperature data
Temp2 = xlsread(filename,sheet2,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time2(1));
L2=datenum(Date_Time2(end));
plot(Date_Time2,Temp2)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 25])
export_fig SureChill_Temp_Data2.jpg

%Plotting Intial Cooldown Power Consumption Data

%Extracting Power Data

xlRange = 'E2:E3898'; %Range for SureChill power consumption data
```

```
Power2 = xlsread(filename,sheet2,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
xlabel('Date')
ylabel('Solar Array Power Production [W]')
L1=datenum(Date_Time2(1));
L2=datenum(Date_Time2(end));
plot(Date_Time2,Power2)
xlim([L1,L2])
export_fig SureChill_Power_Data2.jpg
```

SureChill Field Data

```
%SureChill Field Data Graphing
%% Anegundi Logistimo
%Opening Excel workbook
clc
clear
close all
filename = 'SureChill_Anegundi_Data.xlsx';

%Extracting Dates
sheet = 1;
xlRange = 'A2:A16018'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B16018'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('Anegundi PHC SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 30])

export_fig SureChill_Anegundi_Data.jpg

%% Gumballi Hand Recorded
%Opening Excel workbook
clc
clear
close all
filename = 'KT_PHC_SureChill_Temperature_Data.xlsx';

%Extracting Dates
sheet = 1;
```

```
xlRange = 'A2:A59'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B59'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('Gumballi PHC Hand Recorded SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 10])

export_fig SureChill_Gumballi_Hand_Data.jpg

%% GH Koppa Hand Recorded
%Opening Excel workbook
clc
clear
close all
filename = 'KT_PHC_SureChill_Temperature_Data.xlsx';

%Extracting Dates
sheet = 2;
xlRange = 'A2:A559'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B559'; %Range for SureChill temperature data
```

```
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('GH Koppa PHC Hand Recorded SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 10])

export_fig SureChill_GH_Koppa_Hand_Data.jpg

%% Kannur Hand Recorded
%Opening Excel workbook
clc
clear
close all
filename = 'KT_PHC_SureChill_Temperature_Data.xlsx';

%Extracting Dates
sheet = 3;
xlRange = 'A2:A563'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B563'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('Kannur PHC Hand Recorded SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
```

```
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 10])

export_fig SureChill_Kannur_Hand_Data.jpg


%% SRR Pura Hand Recorded
%Opening Excel workbook
clc
clear
close all
filename = 'KT_PHC_SureChill_Temperature_Data.xlsx';

%Extracting Dates
sheet = 5;
xlRange = 'A2:A481'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B481'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('SRR Pura PHC Hand Recorded SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 10])

export_fig SureChill_SRR_Pura_Hand_Data.jpg

%% Anegundi Hand Recorded
%Opening Excel workbook
clc
```

```
clear
close all
filename = 'KT_PHC_SureChill_Temperature_Data.xlsx';

%Extracting Dates
sheet = 6;
xlRange = 'A2:A243'; %Range for date values
Date_Time = xlsread(filename,sheet,xlRange);
Date_Time = datetime(Date_Time,'ConvertFrom','excel');

%Setting SureChill Temperature Limits
x1 = Date_Time(1);
x2 = Date_Time(end);
y1 = 8;
y2 = 2;

%Extracting Temperature Data
xlRange = 'B2:B243'; %Range for SureChill temperature data
Temp = xlsread(filename,sheet,xlRange);

figure
hold on
grid on
grid minor
set(gca,'fontsize',13,'XTickLabelRotation',65)
title('Anegundi PHC Hand Recorded SureChill Temperature Data')
xlabel('Date')
ylabel('SureChill Temperature [C]')
L1=datenum(Date_Time(1));
L2=datenum(Date_Time(end));
plot(Date_Time,Temp)
plot([x1, x2], [y1, y1],'r')
plot([x1, x2], [y2, y2],'r')
xlim([L1,L2])
ylim([0 21])

export_fig SureChill_Anegundi_Hand_Data.jpg
```

```
%Solar Boat Ambulance Justification
clear
clc
close all
%% Given Information
%General
Ts_Power = 5.0000e-05; %Taken from other Simulink model for charge controller
Ts_Control = 1.0000e-04; %Taken from other Simulink model for charge controller
pf=1; %Power factor

%Motor Data
Num_mot = 2; %Number of motors
Knots_1 = 6; %Lower operating speed [knots]
Knots_2 = 7; %Higher operating speed [knots]
Speed_1 = Knots_1*0.514444; %Lower operating speed [m/s]
Speed_2 = Knots_2*0.514444; %Operating speed [m/s]
P_1 = 3; %Rated motor power at speed 1 [kW]
P_2 = 5; %Rated motor power at speed 2 [kW]
Eff_m = 0.92; %Motor efficiency
V_m = 32; %Motor voltage [V]
Freq_m = 114; %Motor frequency [Hz]
Torque_m = 15.98; %Motor torque [Nm]
I_m = 104; %Motor current [A]
P_m1 = P_1/Eff_m; %Motor power for speed 1 [kW]
P_m2 = P_2/Eff_m; %Motor power for speed 2 [kW]

%Solar System Data
P_solar = 4; %Rated power of solar array [kW]
A_panel = 1.62855; %Panel area [m^2]
Num_panel = 16; %Number of panels
Eff_panel = .1535; %Panel efficiency
Eff_charge = 1; %Charge controller efficiency
I_sc = 8.60; %Short circuit current [A]
V_oc = 37.10; %Open circuit voltage [V]
I_mp = 8.20; %Maximum power current [A]
V_mp = 30.50; %Maximum power voltage [V]

%Battery Data
Num_bat = 2; %Number of batteries
Bat_cap = 72; %Battery nominal capacity [Ah]
Bat_en = 3.686; %Battery nominal energy [kWh]
V_bat = 51.2; %Battery voltage [V]
Bat_DoD = 0.80; %Battery depth of discharge
C_charge = 0.45; %C rate of charging (no load)
Eff_inv = .9; %Inverter efficency [%]
E_bat_real = Bat_en*Bat_DoD*Num_bat;

%Additional Loads & Calculations
P_LED_unit = 12;
Num_LED = 10;
P_LED = P_LED_unit*Num_LED; %Total power of LEDs [W]
```

```
i_LED = P_LED/V_bat; %Current draw of LEDs [A]
%Run time equal to trip time

P_navlights_unit = 25;
Num_navlights = 5;
P_navlights = P_navlights_unit*Num_navlights; %Total power of navigational lights
    [W]
i_navlights = P_navlights/V_bat; %Current draw of navigational lights [A]

P_search_unit = 250;
Num_search = 1;
P_search = P_search_unit*Num_search; %Total power of search lights [W]
i_search = P_search/V_bat; %Current draw of search lights [A]

P_wipe_unit = 100;
Num_wipe = 1;
P_wipe = P_wipe_unit*Num_wipe; %Total power of wiper motors [W]
i_wipe = P_wipe/V_bat; %Current draw of wiper motors [A]

P_horn_unit = 100;
Num_horn = 1;
P_horn = P_horn_unit*Num_horn; %Total power of horn [W]
i_horn = P_horn/V_bat; %Current draw of horn [A]

P_phone_unit = 4;
Num_phone = 2;
P_phone = P_phone_unit*Num_phone; %Total power of phone charging [W]
i_phone = P_phone/V_bat; %Current draw of phone charging [A]

P_spare_unit = 300;
Num_spare = 1;
P_spare = P_spare_unit*Num_spare; %Total power of other spare components [W]
i_spare = P_spare/V_bat; %Current draw of spare components [A]

P_extra_loads = P_LED+P_navlights+P_search+P_wipe+P_horn+P_phone+P_spare; %Total
    power of extra loads [W]

%Medical Loads & Calculations
P_suction_unit = 45;
Num_suction = 1;
P_suction = P_suction_unit*Num_suction; %Total power of portable suction unit [W]
i_suction = P_suction/V_bat; %[A]

P_head_lamp_unit = 5;
Num_head_lamp = 2;
P_head_lamp = P_head_lamp_unit*Num_head_lamp; %Total power of head lamps [W]
i_head_lamp = P_head_lamp/V_bat; %[A]

P_nebulizer_unit = 150;
Num_nebulizer = 1;
P_nebulizer = P_nebulizer_unit*Num_nebulizer; %Total power of nebulizers [W]
i_nebulizer = P_nebulizer/V_bat; %[A]
```

```
P_BP_unit = 120;
Num_BP = 1;
P_BP = P_BP_unit*Num_BP; %Total power of blood pressure unit [W]
i_BP = P_BP/V_bat;

P_ECG = 150;
Num_ECG = 1;
P_ECG = P_ECG*Num_ECG; %Total power of electrocardiography machine [W]
i_ECG = P_ECG/V_bat;

P_medical_loads = P_suction+P_head_lamp+P_nebulizer+P_BP+P_ECG; %Total power of
    medical loads [W]
%% Solar & Temperature Data

%Average Ambient Air Temperature Data (From NASA)
Temp = [20.1, 23.2, 27.1, 28.5, 29.9, 27.5, 25.6, 25.0, 24.9, 23.7, 21.6, 19.5,
    24.7]; %[C]

%Average Global Horizontal Irradiation Data [kWh/m^2*day] (From NREL &
%NASA)
GHI = [4.88, 5.61, 6.12, 6.48, 6.19, 4.43, 3.57, 3.51, 4.24, 4.81, 4.75, 4.63];

%Average Time of Sunrise Each Month [hrs] (taken on the 15th of every month in
    2017)
Sunrise = [6.6, 6.4666, 6.1333, 5.7, 5.41666, 5.35, 5.5, 5.666, 5.78333, 5.9,
    6.11666, 6.41666] ;
Sunrise_sec = Sunrise*3600; %[sec]
%Average Time of Sunset Each Month [hrs] (taken on the 15th of every month in
    2017)
Sunset = [17.68333, 17.98333, 18.15, 18.28333, 18.45, 18.65, 18.68333, 18.4666,
    18.05, 17.61666, 17.35, 17.4] ;
Sunset_sec = Sunset*3600; %[sec]
%Daylight Duration [hrs]
%Daylight = [11.08333, 11.51666, 12.01666, 12.5666, 13.0333, 13.28333, 13.18333,
    12.78333, 12.25, 11.71666, 11.21666, 10.9666];
Daylight = Sunset-Sunrise;
Daylight_sec = Daylight*3600; %[sec]

%Converting GHI to [kW/m^2*day]
I = GHI./Daylight;

%% User Inputs
prompt = {'Enter travel distance [km]','Enter travel speed [knots]','Enter current
     battery state of charge [%]','Enter number of month [e.g. Oct = 10]', 'Enter
    start time [e.g. 13:30]'};
dlg_title = 'Trip Details';
num_lines = 1;
defaultans = {'5','6','100','7','07:30'};
answer = inputdlg(prompt,dlg_title,num_lines,defaultans);
D = str2num(answer{1});
x = str2num(answer{2});
SOC = str2num(answer{3});
month = str2num(answer{4});
```

```
[y, m, d, h, mn, s] = datevec(answer{5});
start_time = h*3600+mn*60+s; %start time in seconds
Temp = Temp(month); %Set ambient temperature data for Simulink Model

%% Solar Irradiation Calculations
T = 86400; %The length of 1 period (length of a day) [sec]
fc = 1/T; %Frequency [Hz]
t = 1:1:T; %Time vector [s]
conversion = 2*pi/T;
Min_sunrise = min(Sunrise_sec);
Max_sunset = max(Sunset_sec);

%Plotting All Month's Solar Irradiation Data
figure
hold on
grid on
%title('Average Daily Solar Irradiance in Each Month')
xlabel('Time of Day [hr]') % x-axis label
ax = gca;
ax.XTick = [18000 21600 25200 28800 32400 36000 39600 43200 46800 50400 54000 57600 61200 64800 68400];
ax.XTickLabel = {'5:00','6:00','7:00','8:00','9:00','10:00','11:00', '12:00', '13:00', '14:00', '15:00', '16:00', '17:00', '18:00', '19:00'};
ylabel('Average Solar Irradiance [kW/m^2]') % y-axis label
set(gca,'fontsize',13,'XTickLabelRotation',65)
xlim([Min_sunrise-3600, Max_sunset+3600])
ylim([0 1])

for i=1:6
        I_peak = pi*I(i)/2; %Peak GHI required to have the set average value [kWh/m2*day]
        offset = Sunrise_sec(i)*(conversion);
        I_day = (I_peak)*(sin(2*pi*fc*t-offset)); %Vector of GHI data throughout average day of specified month [kWh/m^2*day]

        plot(t,I_day) %mean(ans(:,2)) highlight plot data and use to make sure average value is correct
end

for i=7:12
        I_peak = pi*I(i)/2; %Peak GHI required to have the set average value [kWh/m2*day]
        offset = Sunrise_sec(i)*(conversion);
        I_day = (I_peak)*(sin(2*pi*fc*t-offset)); %Vector of GHI data throughout average day of specified month [kWh/m^2*day]

        plot(t,I_day,'--') %mean(ans(:,2)) highlight plot data and use to make sure average value is correct
end
legend('Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec')
export_fig Irradiance_Month.jpg

%Setting Month Titles
```

```
if month==1
    m='January';
elseif month==2
    m='February';
elseif month==3
    m='March';
elseif month==4
    m='April';
elseif month==5
    m='May';
elseif month==6
    m='June';
elseif month==7
    m='July';
elseif month==8
    m='August';
elseif month==9
    m='September';
elseif month==10
    m='October';
elseif month==11
    m='November';
elseif month==12
    m='December';
end

%Recalculating for Specified Month and Plotting Separately
for i=1:12
    if month==i
        I_peak = pi*I(i)/2; %Peak GHI required to have the set average value [kWh/m2*day]
        offset = Sunrise_sec(i)*(conversion);
        Sunrise_Calc = Sunrise_sec(i); %Setting sunrise value for later [s]
        Sunset_Calc = Sunset_sec(i); %Setting sunset value for later [s]
        I_day = (I_peak)*(sin(2*pi*fc*t-offset)); %Vector of GHI data throughout average day of specified month [kWh/m^2*day]

        figure
        hold on
        grid on
        %str = sprintf('Average Solar Irradiance in %s', m);
        %title(str)
        xlabel('Time of Day [hr]') % x-axis label
        ax = gca;
        ax.XTick = [18000 21600 25200 28800 32400 36000 39600 43200 46800 50400 54000 57600 61200 64800 68400];
        ax.XTickLabel = {'5:00','6:00','7:00','8:00','9:00','10:00','11:00', '12:00', '13:00', '14:00', '15:00', '16:00', '17:00', '18:00', '19:00'};
        ylabel('Average Solar Irradiance [kW/m^2]') % y-axis label
        set(gca,'fontsize',13,'XTickLabelRotation',65)
        xlim([Sunrise_sec(i)-3600, Sunset_sec(i)+3600])
        ylim([0 1])
        plot(t,I_day) %mean(ans(:,2)) highlight plot data and use to make sure
```

```
average value is correct

    end
end

I_day = I_day*1000; %Converting I_day to [W/m^2] for Simulink
%% Boat Performance Calculations for Trip

switch x
    %Calculations for traveling at 6 knots
    case 6
        Speed = Speed_1; %Setting case
        t_minutes =(D*1000)/Speed/60; %Travel time [min] 790.9998minutes daylight 146.49km
        t_hrs = t_minutes/60; %Travel time [hrs]
        t_sec = round(t_minutes*60); %Travel time [s] rounded to nearest second
        end_time = start_time+t_sec; %End time [s]

        t_trip = start_time:1:end_time; %Create a vector for trip time for Simulink [s]
        I_trip = I_day(start_time:end_time);%Calculating the irradiation over the time of the trip for Simulink modeling [W/m^2]

        figure
        hold on
        grid on
        title('Time of Trip vs. Irradiance During Trip')
        xlabel('Time [hr]') % x-axis label
        ylabel('Solar Irradiance [kW/m^2]') % y-axis label
        set(gca,'fontsize',13)
        plot(t_trip,I_trip)
        export_fig Irradiance_Trip_6.jpg

        P_m = P_m1; %Set a variable for motor power [kW]
        P_req = (P_m*Num_mot)/(Eff_inv*pf); %Power required for motors [kW]
        i_req = (P_req/2*1000)/V_m*sqrt(3)*pf; %Required current per motor [A]
        E_req = (P_req*D*1000)/(Speed*3600); %Energy required [kWh]

        E_start = .01*SOC*E_bat_real; %Starting energy [kWh]

        fun = @(t) (I_peak)*(sin(2*pi*fc*t-offset)); %Solar irradiance function [kW/m^2]
        I_full = integral(fun,Sunrise_Calc, Sunset_Calc); %Solar irradiance over day [kWs/m^2]
        I_full = I_full/3600; %Cover to [kWh/m^2]
        q = integral(fun,start_time,end_time); %Solar irradiance over trip [kWs/m^2]
        q = q/3600; %Convert to [kWh/m^2]
        I_ratio = q/I_full; %Ratio of irradiance during trip
        Panel_Properties = A_panel*Num_panel*Eff_panel*Eff_charge; %Given solar panel properties
        E_solar = q*Panel_Properties; %Energy produced by solar array during trip [kWh]
```

```
        %Plotting integral under irradiance curve
        x = linspace(start_time,end_time);
        y1 = (I_peak)*(sin(2*pi*fc*x-offset));
        figure(2)
        h=area(x,y1);
        h.FaceColor = [1 0 0];
        export_fig Irradiance_Month_Specific.jpg

        C_rate = E_bat_real/(1/.45)/3600; %Rate of charge/discharge of battery [kWh/s]
        %Charge_time = SOC./C_rate; %Recharge time (hrs)

        %Calculating the state of charge through the day
        Discharge = (E_req/t_sec)/E_bat_real; %Discharge rate for travel speed [% charge/s]
        Recharge = (E_solar/t_sec)/E_bat_real; %Recharge rate for solar conditions [%charge/s]


    %Calculations for traveling at 7 knots
    case 7
        Speed = Speed_2; %Setting case
        t_minutes =(D*1000)/Speed/60; %Travel time [min]
        t_hrs = t_minutes/60; %Travel time [hrs]
        t_sec = round(t_minutes*60); %Travel time [s] rounded to nearest second
        end_time = start_time+t_sec; %End time [s]

        t_trip = start_time:1:end_time; %Create a vector for trip time for Simulink [s]
        I_trip = I_day(start_time:end_time);%Calculating the irradiation over the time of the trip for Simulink modeling [W/m^2]
        figure
        set(gca,'fontsize',13)
        plot(t_trip,I_trip)
        export_fig Irradiance_Trip_7.jpg

        P_m = P_m2; %Set a variable for motor power [kW]
        P_req = (P_m*Num_mot)/(Eff_inv*pf); %Power required for motors [kW]
        i_req = (P_req/2*1000)/V_m*sqrt(3)*pf; %Required current per motor [A]
        E_req = (P_req*D*1000)/(Speed*3600); %Energy required [kWh]

        E_start = .01*SOC*E_bat_real; %Starting energy [kWh]

        fun = @(t) (I_peak)*(sin(2*pi*fc*t-offset)); %Solar irradiance function [kW/m^2]
        I_full = integral(fun,Sunrise_Calc, Sunset_Calc); %Solar irradiance over day [kWs/m^2]
        I_full = I_full/3600; %Cover to [kWh/m^2]
        q = integral(fun,start_time,end_time); %Solar irradiance over trip [kWs/m^2]
        q = q/3600; %Convert to [kWh/m^2]
        I_ratio = q/I_full; %Ratio of irradiance during trip
```

```
        Panel_Properties = A_panel*Num_panel*Eff_panel*Eff_charge; %Given solar panel properties
        E_solar = q*Panel_Properties; %Energy produced by solar array during trip [kWh]

        %Plotting integral under irradiance curve
        x = linspace(start_time,end_time);
        y1 = (I_peak)*(sin(2*pi*fc*x-offset));
        figure(2)
        h=area(x,y1);
        h.FaceColor = [1 0 0];
        export_fig Irradiance_Month_Specific.jpg

        C_rate = E_bat_real/(1/.45)/3600; %Rate of charge/discharge of battery [kWh/s]
        %Charge_time = SOC./C_rate; %Recharge time (hrs)

        %Calculating the state of charge through the day
        Discharge = (E_req/t_sec)/E_bat_real; %Discharge rate for travel speed [%charge/s]
        Recharge = (E_solar/t_sec)/E_bat_real; %Recharge rate for solar conditions [%charge/s]

    otherwise; disp('The boat cannot run at this speed')
end

% Adding in run times and percentages of external devices
t_LED = t_sec; %Running time of LEDs [s]
if t_sec <= t_LED
    t_LED = .99*t_sec;
end
prct_LED = (t_LED/t_sec)*100;

t_navlights = t_sec; %Running time of navigational lights [s]
if t_sec <= t_navlights
    t_navlights = .99*t_sec;
end
prct_navlights = (t_navlights/t_sec)*100;

t_search = (1/8)*t_sec; %Running time of search lights [s]
if t_sec <= t_search
    t_search = .99*t_sec;
end
prct_search = (t_search/t_sec)*100;

t_wipe = (1/4)*t_sec; %Running time of windshield wipers [s]
if t_sec <= t_wipe
    t_wipe = .99*t_sec;
end
prct_wipe = (t_wipe/t_sec)*100;

t_horn = 0.10; %Running time of horn [m]
t_horn = t_horn*60; %[s]
```

```
if t_sec <= t_horn
    t_horn = .99*t_sec;
end
prct_horn = (t_horn/t_sec)*100;

t_phone = t_sec; %Running time of phone chargers [s]
if t_sec <= t_phone
    t_phone = .99*t_sec;
end
prct_phone = (t_phone/t_sec)*100;

t_spare = (1/8)*t_sec; %Running time of spare components [s]
if t_sec <= t_spare
    t_spare = .99*t_sec;
end
prct_spare = (t_spare/t_sec)*100;

% Adding in run times and percentages of medical devices

t_suction = 15; %Running time of suction apparatus per patient [m]
t_suction = t_suction*60; %[s]
if t_sec < t_suction
    t_suction = t_sec;
end
prct_suction = (t_suction/t_sec)*100; %[%]

t_head_lamp = 30; %Running time of head lamps per patient [m]
t_head_lamp = t_head_lamp*60; %[s]
if t_sec <= t_head_lamp
    t_head_lamp = .99*t_sec;
end
prct_head_lamp = (t_head_lamp/t_sec)*100;

t_nebulizer = 15; %Running time of nebulizer per patient [m]
t_nebulizer = t_nebulizer*60; %[s]
if t_sec <= t_nebulizer
    t_nebulizer = .99*t_sec;
end
prct_nebulizer = (t_nebulizer/t_sec)*100;

t_BP = 5; %Running time of blood pressure unit per patient [m] could be 3 times
    per trip
t_BP = t_BP*60; %[s]
if t_sec <= t_BP
    t_BP = .99*t_sec;
end
prct_BP = (t_BP/t_sec)*100;

t_ECG = 10; %Running time of EKG machine per patient [m]
t_ECG = t_ECG*60; %[s]
if t_sec <= t_ECG
    t_ECG = .99*t_sec;
end
```

```
prct_ECG = (t_ECG/t_sec)*100;

%if E_end<0
%          h = msgbox('Not enough energy in battery for this trip', 'Warning','error');
%end

%% Travel Distance Plots

%Plotting Minimum Daily Travel Distance vs. State of Charge (Assumes no
%charging from Solar PV
SOC_Plot = (0:0.1:100);

D_min_6 = ((.01*SOC_Plot*E_bat_real)*(Speed_1*3600*Eff_inv*Eff_m*pf))/(P_m1*Num_mot*1000); %Minimum daily travel distance at 6 knots with SOC and no recharging [km]
D_min_7 = ((.01*SOC_Plot*E_bat_real)*(Speed_2*3600*Eff_inv*Eff_m*pf))/(P_m2*Num_mot*1000); %Minimum daily travel distance at 7 knots with SOC and no recharging [km]

figure
hold on
grid on
title('State of Charge vs. Maximum Travel Distance with No Solar Charging at 6 knots')
xlabel('Original State of Charge [%]') % x-axis label
ylabel('Maximum Travel Distance [km]') % y-axis label
set(gca,'fontsize',13)
plot(SOC_Plot,D_min_6,SOC_Plot,D_min_7)
legend('@ 6 knots','@ 7 knots','location','northwest')
export_fig Minimum_Trip.jpg

%Plotting Maximum Daily Travel Distance vs. State of Charge for diffent months of
%the year with different average GHIs. Traveling at max speed (6 knots).
%Theoretical value, may require several periods of stopping and charging
%throughout the day, therefore travel time may be high.

figure
hold on
grid on
%title('SOC vs. Maximum Daily Travel Distance for Different Months at 6 knots')
xlabel('Original State of Charge [%]') % x-axis label
ylabel('Maximum Daily Travel Distance (km)') % y-axis label
set(gca,'fontsize',13)

for i=1:6
    Max_D_Plot = ((.01*SOC_Plot*E_bat_real)+(GHI(i)*Panel_Properties)).*(Speed_1.*3600.*Eff_inv.*Eff_m.*pf)./(P_m1.*Num_mot.*1000);
    plot(SOC_Plot,Max_D_Plot);
end
for i=7:12
    Max_D_Plot = ((.01*SOC_Plot*E_bat_real)+(GHI(i)*Panel_Properties)).*(Eff_inv.*Eff_m.*pf.*Speed_1*3600)./(P_m1*Num_mot*1000);
```

```
    plot(SOC_Plot,Max_D_Plot,'--');
end
legend('Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec','location','northeastoutside')
export_fig Maximum_Trip_6.jpg

%Plotting Maximum Daily Travel Distance vs. State of Charge for diffent months of
%the year with different average GHIs. Traveling at max speed (6 knots).
%Theoretical value, may require several periods of stopping and charging
%throughout the day, therefore travel time may be high.

figure
hold on
grid on
%title('SOC vs. Maximum Daily Travel Distance for Different Months at 7 knots')
xlabel('Original State of Charge [%]') % x-axis label
ylabel('Maximum Daily Travel Distance (km)') % y-axis label
set(gca,'fontsize',13)

for i=1:6
    Max_D_Plot = ((.01*SOC_Plot*E_bat_real)+(GHI(i)*Panel_Properties)).*(Speed_2.*3600.*Eff_inv.*Eff_m.*pf)./(P_m2.*Num_mot.*1000);
    plot(SOC_Plot,Max_D_Plot);
end
for i=7:12
    Max_D_Plot = ((.01*SOC_Plot*E_bat_real)+(GHI(i)*Panel_Properties)).*(Eff_inv.*Eff_m.*pf.*Speed_2*3600)./(P_m2*Num_mot*1000);
    plot(SOC_Plot,Max_D_Plot,'--');
end
legend('Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec','location','northeastoutside')
export_fig Maximum_Trip_7.jpg

%% Simulink Print Figure Names
% export_fig SOC_Trip.jpg
% export_fig PV_Generation.jpg
% export_fig Motor_Usage.jpg
```

Boat Ambulance Cost Calculations

```
clear
clc
close all

%% Kerosene Boat Costs
Daily_Op_Cost = 400; %[rupee]
Monthly_Maintenance_Cost = 1500;%[rupee]
Yearly_Cost = ((Monthly_Maintenance_Cost*12)+(Daily_Op_Cost*365))/100000; %[lakh rupee/year]
Opportunity_Cost = Yearly_Cost*.25; %Costs from not running for 1 week a month[lakh rupee/year]
t= (0:.01:40); %[years]
Cumul_Cost = (Yearly_Cost+Opportunity_Cost)*t + 2.078*heaviside(t-8.3)+2.078*heaviside(t-8.3*2)+2.078*heaviside(t-8.3*3)+2.078*heaviside(t-8.3*4)+2.078*heaviside(t-8.3*5)+2.078*heaviside(t-8.3*6); %[lakh rupee/year]

%% NavAlt Solar Boat Costs
NavAlt_Cost1 = 47.5;
NavAlt_Cost2 = 59.5;
Daily_Op_Cost_NavAlt = Daily_Op_Cost*.1;
Monthly_Maintenance_Cost_NavAlt = Monthly_Maintenance_Cost*.25;
Yearly_Cost_NavAlt = ((Monthly_Maintenance_Cost_NavAlt*12)+(Daily_Op_Cost_NavAlt*365))/100000;
Solar_Boat_Cost1 = NavAlt_Cost1 + (Yearly_Cost_NavAlt*t) + 1.7*heaviside(t-4)+1.7*heaviside(t-4*2)+1.7*heaviside(t-4*3)+1.7*heaviside(t-4*4)+1.7*heaviside(t-4*5)+1.7*heaviside(t-4*6)+1.7*heaviside(t-4*7)+1.7*heaviside(t-4*8)+1.7*heaviside(t-4*9)+1.7*heaviside(t-4*10)+1.7*heaviside(t-4*11)+1.7*heaviside(t-4*12)+1.7*heaviside(t-4*13)+1.7*heaviside(t-4*14)+1.7*heaviside(t-4*15)+1.7*heaviside(t-4*16)+1.7*heaviside(t-4*17)+1.7*heaviside(t-4*18)+1.7*heaviside(t-4*19)+1.7*heaviside(t-4*20)+1.7*heaviside(t-4*21)+1.7*heaviside(t-4*22)+1.7*heaviside(t-4*23); %[lakh]
Solar_Boat_Cost2 = NavAlt_Cost2 + (Yearly_Cost_NavAlt*t) + 2.25*heaviside(t-4)+2.25*heaviside(t-4*2)+2.25*heaviside(t-4*3)+2.25*heaviside(t-4*4)+2.25*heaviside(t-4*5)+2.25*heaviside(t-4*6)+2.25*heaviside(t-4*7)+2.25*heaviside(t-4*8)+2.25*heaviside(t-4*9)+2.25*heaviside(t-4*10)+2.25*heaviside(t-4*11)+2.25*heaviside(t-4*12)+2.25*heaviside(t-4*13)+2.25*heaviside(t-4*14)+2.25*heaviside(t-4*15)+2.25*heaviside(t-4*16)+2.25*heaviside(t-4*17)+2.25*heaviside(t-4*18)+2.25*heaviside(t-4*19)+2.25*heaviside(t-4*20)+2.25*heaviside(t-4*21)+2.25*heaviside(t-4*22)+2.25*heaviside(t-4*23); %[lakh]

% for i=0:length(t)
%
%     Solar_Boat_Cost_Test = NavAlt_Cost1 + 1.7*heaviside(t-4*i);
% end

%% Plotting
Y2 = zeros(1,length(t));
Y2(:) = NavAlt_Cost1;

Y3 = zeros(1,length(t));
Y3(:) = NavAlt_Cost2;
```

```

figure
hold all
grid on
%title('Boat Ambulance Cost Over Time')
xlabel('Time [years]') % x-axis label
ylabel('Cost [lakh rupee]') % y-axis label
plot(t,Cumul_Cost,t,Solar_Boat_Cost1,t,Solar_Boat_Cost2,t,Y2,'--',t,Y3,':')
%refline(0,47.5);

idx = find(Solar_Boat_Cost1 - Cumul_Cost < eps, 1);
px = t(idx);
px = round(px);
py = Cumul_Cost(idx);
py = round(py);
txt = sprintf('%d years %d lakh rupee',px,py);
text(px,py,txt,'HorizontalAlignment','left','VerticalAlignment','top')
plot(px, py, 'r*', 'MarkerSize', 2)


idx = find(Solar_Boat_Cost2 - Cumul_Cost < eps, 1);
px = t(idx);
px = round(px);
py = Cumul_Cost(idx);
py = round(py);
txt = sprintf('%d years %d lakh rupee',px,py);
text(px,py,txt,'HorizontalAlignment','left','VerticalAlignment','top')
plot(px, py, 'r*', 'MarkerSize', 2)


idx = find(Y3 - Cumul_Cost < eps, 1);
px = t(idx);
px = round(px);
py = Cumul_Cost(idx);
py = round(py);
txt = sprintf('%d years %d lakh rupee',px,py);
text(px,py,txt,'HorizontalAlignment','left','VerticalAlignment','top')
plot(px, py, 'r*', 'MarkerSize', 2)

idx1 = find(Y2 - Cumul_Cost < eps, 1);
px1 = t(idx1);
px1 = round(px1);
py1 = Cumul_Cost(idx1);
py1 = round(py1);
txt = sprintf('%d years %d lakh rupee',px1,py1);
text(px1,py1,txt,'HorizontalAlignment','left','VerticalAlignment','top')
plot(px1, py1, 'r*', 'MarkerSize', 2)
set(gca,'fontsize',13)
%set(hline,'LineStyle','--')
legend('Cumulative Kerosene Boat Costs','Cumulative Design 1 Cost','Cumulative Design 2 Cost','Initial Cost of Design 1','Initial Cost of Design 2','Location','northwest')

```

```
export_fig Cost_Over_Time.jpg
```